THE APPLICATION OF STABLE CARBON ISOTOPES AS AN ENHANCED METHOD FOR STATISTICAL CROSSDATING: A CASE STUDY FROM RANGE CREEK CANYON, UTAH

by

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STATEMENT OF THESIS APPROVAL

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ABSTRACT

Dendroarcheological samples pose a particular challenge when attempting to crossdate them against a master chronology. Previous attempts to accurately crossdate dendroarcheological samples from Range Creek Canyon have had limited success (Towner et al. 2009), due in part to the nonsignificance of the master chronology compared to the relatively long period spanning prehistoric occupation, and the limited size of the building materials selected by the Fremont inhabitants. In an attempt to increase the statistical significance of a chronology, and thus increase the success of crossdating dendroarcheological materials, we built two chronologies from a more sensitive species, *J. osteosperma* (Utah juniper), using both ring width and stable carbon isotopes. The use of a more sensitive species than previous attempts yielded one additional marker year, resulting in a 3.125% increase. The isotope chronology identified an additional three marker years, yielding a 9.375% increase in marker years over ring width alone and a total 12.5% increase when combined into a multivariate chronology, suggesting that including other variables should be a priority for problematic dendroarcheological studies. Using multiple variables in a chronology allows the use of alternative signal matching techniques, e.g. Principal Component Analysis (PCA), to explore several underlying signals rather than just the extremes of one response function. We explored the underlying structure of the two variables using a PCA and report on its potential strength for more advanced crossdating than traditional visual methods. Finally, we provide recommendations for future dendroarchaeological research conducted in Range Creek Canyon.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Range Creek Canyon, Utah, is one of the best preserved Fremont archeological records in North America. The canyon was inhabited by the Fremont from ~AD 500 to AD 1350 (Green, 2008; Spangler et al., 2004) with peak occupation occurring between AD 950 to AD 1200 (Green, 2008). The remote nature of the canyon, coupled with the unique historical ownership resulted in an unparalleled preservation of archeological remnants (Jones et al., 2002; Jones et al., 2005). Despite the large amount of archeological materials recovered from the canyon, many questions remain unanswered about the Fremont inhabitants and the history of the canyon during occupation. What was the rate and pattern of dispersal throughout the canyon (Green, 2011; Jones & Boomgarden, 2012)? What was the climate like? What caused the sudden abandonment of the canyon (Jones & Boomgarden, 2012)?

Attempts to address many of these questions have employed traditional paleo-environmental methods, all with significant limitation and mixed results. Lithological and palynological studies have been hampered by reversals in age models derived from ^{14}C dating due to contamination problems likely driven by large deposits of bitumen or kerogen in close proximity to the canyon, and are limited in temporal resolution (Brunelle et al., 2011; Gwynn and Hanson, 2007). While pack-rat middens have provided some insight into the climate of the region, the coarse resolution of the proxy is unable to provide information about variability over a narrow window of time (Coats et al., 2008).

Further complicating the matter, from AD 1000 to 1200 the natural production of ^{14}C decreased globally, resulting in large statistical uncertainty associated with the calibrated age of materials dated during this period (van der Plicht, 2005). This radiocarbon plateau spans much of the duration of occupation, and results in a +/- 200 year uncertainty. Thus, the resolution of traditional ^{14}C dating of archeological materials is not high enough to explore questions of dispersal and abandonment (Spangler & Metcalfe., 2002; Metcalfe, 2011).

Dendrochronology is a logical source for a paleoenvironmental proxy not reliant on ^{14}C dates with a high enough resolution to address questions of occupation, dispersal and abandonment. This is due to the fact it offers near annual resolution and directly datable chronology.

The number of species of trees in Range Creek is limited. *Juniperus osteosperma* (Utah juniper) is the dominant species, with some *Pseudotsuga menziesii* (Douglas fir) and very few *Pinus edulis* (Pinyon) found on the slopes of the canyon (Yentsch et al., 2010).

While *P. menziesii* is the most useful dendrochronological species due to its regular growth structure, and the availability of the nearby Harmon Canyon master chronology (Knight et al., 2010; Towner et al., 2009), previous attempts to use this species in the canyon have had little success. Towner et al., 2009 attempted to crossdate 197 dendroarchaeological samples collected from Fremont structures in the canyon, and had a success rate of only 8%. This low success rate was due to the complacency of the master chronology when compared to the relatively long period of occupation (A.D 800 – 1300), and due to the fact that most of the materials used in Fremont structures are small, resulting in a limited number of rings to positively match against a master chronology.

As a result of the limitations with *P. menziesii*, the more sensitive species *J. osteosperma* was selected for this study. *J. osteosperma* has traditionally been avoided by the dendrochronological community due to the fact it produces extremely small annual rings and is highly susceptible to the production of false or missing rings. However, the sensitivity of the tree compared to other available tree species, and the increased number of rings in a given radius makes it ideal for the development of a more statistically significant chronology.

Recent advancements in the preparation and analysis of stable isotopes in tree-rings have identified these as additional variables to reconstruct paleo-climatic conditions in well dated chronologies (Gagen et al., 2007; Kern et al., 2013; Leavitt & Long, 1982; Leavitt et al., 2011; Loader et al., 1995; McCaroll & Loader, 2004; Tei et al., 2013; Warren et al., 2001). However, a limited amount of attention has been directed towards the application of stable isotopes in assistance of building more sensitive chronologies, and thus increasing the success rate of crossdating difficult materials.

In this study we produce a 40 year multivariate chronology from five *J. osteosperma* collected from Range Creek, using annual ring width and the distinct ^{13}C values to produce a more statistically significant master chronology. In addition, we explore the use of Principal Components Analysis (PCA) as a more advanced crossdating technique using our multivariate chronology. Peters et al. (1981) introduced the use of PCA in dendrochronology while attempting to increase the correlation of an indexed series to a climatic signal, but this analytical tool has not been widely implemented in the dendrochronological community. Although it is not the goal of this study, we explore possible relationships between our identified principal component indexes and environmental variables to verify that the signals selected for analysis are growth responses and not noise within the larger signal.

It is the goal of this study to address the following four questions and objectives. 1) Does the use of the more sensitive species *J. osteosperma* result in a greater number of identified marker years compared to the Harmon Canyon *P. menziesii* chronology? 2) Does the addition of the second variable, ^{13}C values, increase the statistical significance of the chronology by identifying additional independent marker years? 3) Can the resulting multivariate chronology identify additional indexes by which more advanced crossdating could be performed? 4) Provide recommendations to future dendroarchaeological attempts in Range Creek Canyon based on our findings.

CHAPTER 2

REGIONAL SETTING

Geography

Range Creek Canyon (approximately 39 21' 29"N, 110 07' 45"W) is a North-South oriented canyon located in the northern most extension of the Colorado Plateau physiographic province (Fig. 1). This isolated tributary of the Desolation Canyon expanse of the Green River is situated between the distinct geographic features of the Book Cliffs and the Tavaputs Plateau. The perennial stream, Range Creek, begins at 3048 m (10,000') and terminates at the Green River, approximately 30 miles to the south, at 1280 m (4,200'). The Book Cliffs form the western periphery of the canyon, rising abruptly up to 2595 m (8,514'). The eastern periphery is formed by the Tavaputs Plateau, with elevations exceeding 3050 m (10,000') in places. These two topographic features converge at the northern extent of the canyon in a narrow escarpment situated at 3047 m (9,996').

The geology of Range Creek presents a unique challenge to the dating of sediments. Numerous studies have identified large deposits of bitumen in the Bitukinhouse Sandstone formation found in the upper deposits of the canyon and the surrounding Uintah Basin (Gwynn & Hanson, 2007; Holmes et al., 1956; Holmes & Page, 1956; Remy & Ferrell, 1989). The presence of significantly older, or radiocarbon dead, bitumen in the material being deposited on the canyon floor makes the determination of the "true" radiocarbon age of lithological samples unreliable (Aufderheide et al., 2004; Wright, 1980). Thus the presence of bitumen in the sediments of Range Creek has made it problematic, if not impossible, to produce a reliable age model for lithological or palynological studies.

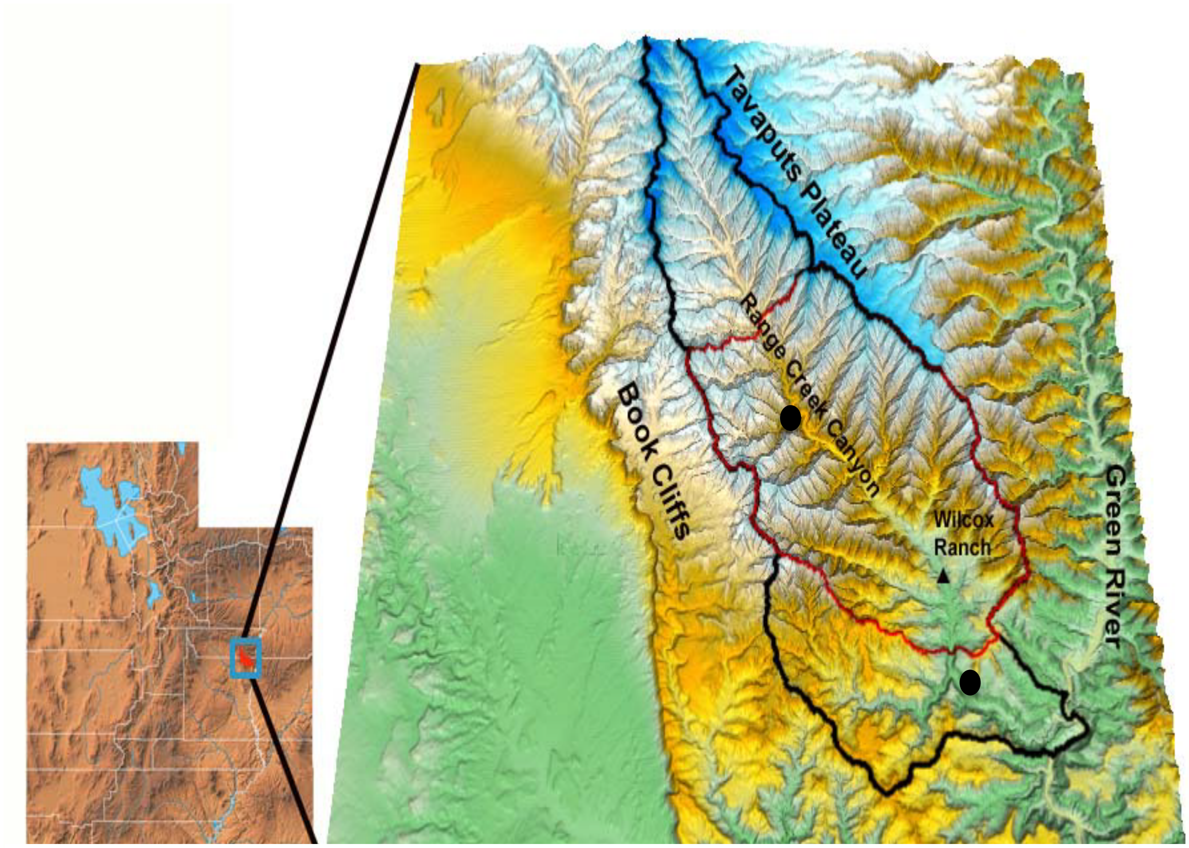

Figure 1 Map of Utah showing the general location of Range Creek. Blue indicates elevations over 2750 m; green indicates elevations under 1300 m. Black line represents hydrological boundary. Red line indicates area of canyon largely protected from public access due to location of field station. Ranch House represented by black triangle. Black dots represent two study sites

Climate

As part of the Colorado Plateau, the modern precipitation regime of Range Creek is defined by a bi-seasonal pattern, with approximately half of the precipitation received from winter storms originating in the Pacific, and half from summer convective storms originating from the Gulf of Mexico. Range Creek is located within the modern zone of influence for the North American Monsoon (NAM), however, just north of the "normal" NAM boundary. Range Creek is positioned at the boundary of four precipitation regimes. Areas to the southeast receive the majority of precipitation in fall, whereas areas to the east are dominated by spring moisture, the west by summer moisture and the northwest by winter precipitation (Mock, 1996). Thus, even minor shifts in the drivers of modern precipitation would affect the seasonal balance of moisture within the area.

Range Creek has a large variation in seasonal temperatures. Summer (June, July, August) is dominated by hot days, with average maximum temperatures of 34.7^{o} C, and relatively cool nights, with an average minimum of 10.9^{o} C. Winters (December, January, February) are considerably colder, with monthly maximum temperatures averaging 9.5^{o} C and minimum temperatures averaging -14.8^{o} C at the Range Creek weather station located on the canyon floor near midcanyon.

Archaeology

Range Creek is one of the best preserved Fremont archeological records in North America. The remote nature of the canyon, coupled with the fact that the central part of the canyon was under private control from 1941 to 2001 by the Wilcox Ranch, results in the excellent preservation of archeological remnants. The canyon was inhabited by the Fremont from ~AD 500 to AD 1350 (Spangler et al., 2004; Green, 2008). Radiocarbon dates on archeological materials indicate that peak occupation occurred between AD 950-1200 (Green, 2008). However, the lack of a detailed chronology means that the timing of demographic changes of the Fremont occupation in the canyon are still poorly understood (Jones et al., 2012; Green, 2011). The development of a reliable detailed chronology would aid in addressing the dispersal patterns of occupation within the canyon, as well as provide a potential proxy for linking occupational changes and abandonment to environmental changes.

The development of a detailed chronology has, to this point, been hindered due to limitations in the calibration of traditional ^{14}C dating (Metcalfe, 2011; Spangler & Metcalfe, 2002). As discussed above, the majority of Fremont occupation occurred during a plateau and reduction of radiocarbon, from 1,000 – 1,200 A.D., which results in large uncertainty around radiocarbon dates in this period. Thus, radiocarbon dating during this period lacks the precision and resolution to accurately address the occupation, expansion, and abandonment of Range Creek by the Fremont.

CHAPTER 3

MATERIALS AND METHODS

Juniperus osteosperma

J. osteosperma is a long-lived, resilient, hardwood species that occupies a vast geographic niche (Lanner, 1984; Loehle, 1988). It grows throughout the arid regions of the southwestern United States, confined between 1,300 – 2,600 meters (Lanner, 1984; Arnold et al., 1964; Hitchcock & Cronquist, 1973). The large range of the species, as well as its ability to grow in harsh arid regions positions *J. osteosperma* to be an excellent recorder of climatic information, resulting in large annual variation of ring width and producing a more informative chronology, thus more distinctive for crossdating, than many other species.

Of equal importance, *J. osteosperma* served as a primary building material for many prehistoric Native American populations (Janetski, 1997), and was the most commonly used material for the Fremont of Range Creek, accounting for 34.8% of the species used in Fremont structures sampled by Towner et al., (2009). It was most likely selected as a building material due to the easy availability as well as the fact that *J. osteosperma* is a very dense hard wood that has few parasites to potentially compromise the strength of the wood. The use of *J. osteosperma* by the Fremont provides abundant sources of material to extend chronologies through occupation. In addition, the material selected for building tends to be limited in radial size, which results in a limited number of rings to crossdate to a master chronology. The slow growth rate of *J. osteosperma* means that the number of rings per sample should be higher than other species, increasing the number of years for a given length of wood.

Despite these numerous advantages, *J. osteosperma* has been generally avoided by the dendrochronological community. This aversion is derived from the limited size of the annual growth rings, as well as the species' tendency to produce missing or false growth rings, which occur when a tree terminates growth due to a deficit in a limiting factor, followed by a re-initiation of growth when said limiting factor returns in a sufficient amount (Speer et al., 2010; Copenheaver et al., 2006). In arid regions, this limiting factor is generally precipitation.

Tree and site sampling

Three trees were sampled from each of the two field sites, one upper canyon and one lower canyon site (Fig. 1), resulting in a total of six cross-sections. One tree was sampled from each side of the canyon and one from the canyon floor, resulting in the collection of samples forming a transect perpendicular to the canyon. The two samples collected from the canyon floor were selected based on size and complacency of signal, while the four samples collected from either side of the canyon were selected based on their size and sensitivity as described by Stokes and Smiley (1968). Due to this diverse sampling strategy a large inter-tree ^{13}C variability is expected (Leavitt & Long, 1984; Leavitt & Lara, 1994; Loader et al., 1995; McCaroll & Pawellek, 1998; Brendel et al., 2002).

Laboratory methods

Cross sections were brought back to the lab at the University of Utah and treated to standard dendrochronological preparation (Stokes & Smiley, 1968). A minimum of two transects per cross-section were examined for consistency in growth structure and compared to increase accuracy in ring width measurements. The transect with the least amount of problem areas was selected and cut into 5x5x1 cm blocks consisting of the longitudinal plane of the tree to remove the radial curve of growth rings (Speer, 2010). A high precision computer controlled micromilling apparatus was used to isolate and grind individual growth rings for isotopic analysis (Dodd et al, 2008; Wurster et al., 1999).

Milled samples were further ground into a homogenous powder when needed, and weighed for isotopic analysis. Some initial studies suggested that it is best to reduce wholewood to cellulose prior to isotopic analysis (Wilson & Grinsted, 1977; Barbour et al., 2002; Loader et al., 2003) because various components of wood are formed through differing biochemical processes and are thus subject to different fractionation events (Wilson & Grinsted 1977, Barbour et al., 2002; Loader et al., 2003). However, there is a growing body of evidence that suggests that any signal associated with components other than cellulose, the dominant component of wood, are negligible (Tei et al., 2013; Loader et al., 2003; McCarroll & Pawellek, 1998; Ponton et al., 2001; Van de Water, 2002; Borella & Leuenberger, 1998; Barbour et al., 2001; Leuenberger et al., 1998; Schleser et al., 1999). This is driven by the fact that the primary factor controlling isotopic variability in tree rings results from variations in climatic conditions, not proportions of the components of wood (McCarroll & Pawellek, 1998; Ponton et al., 2001). Multiple studies have shown that while an offset exists between the isotopic values of cellulose and other components, the variability and frequency of isotopic values are directly linked between components (Leavitt & Long, 1982; Loader et al., 2003). Due to our limited sample size, the quantity of years analyzed, and this growing body of literature, we chose to focus our analysis on wholewood.

Stable isotope analysis was conducted at the Stable Isotope Ratio Facility for Environmental Research (SIRFER) at the University of Utah. Carbon isotopes were analyzed using an Elemental Analyzer (EA) coupled with a Delta Plus Advantage Isotope Ratio Mass Spectrometer (EA-IRMS). A carbon only sequence was employed to allow for the continuous flow on-line measurement despite the extremely limited amount of sample material.

Stable isotope theory

The source for carbon in photosynthetic plants is atmospheric CO_2, thus stomatal openings serve as entry points for the transfer of carbon from the atmosphere into the tree to support photosynthesis. Stomatal openings also serve as the primary source of water loss in a plant. Thus, stomatal openings serve two primary functions; to allow the diffusion of CO_2 into the leaf to support photosynthesis, and to convey water from the plant to the surrounding atmosphere. As a result, a balance must be struck, particularly in arid environments, between photosynthetic rate and stomatal conductance. Both diffusion and photosynthetic enzyme processes favor the fixation of $^{12}CO_2$ over the larger and heavier $^{13}CO_2$ (McCaroll & Loader, 2004). One of the key determining factors in the level of discrimination is stomatal conductance (Farquhar et al., 1982). Thus, in arid environments like Range Creek, under drier than usual conditions the stomatal openings close to reduce water loss, the available CO_2 is reduced, and proportionately more $^{13}CO_2$ will be incorporated. This relationship can be expressed by the following equation.

$$\Delta = a + (b - a)ci/ca$$

where *a* is discrimination resulting from diffusion (~-4.4‰), *b* is discrimination resulting from the photosynthetic enzyme process (~-27‰), *ci* and *ca* are the internal and atmospheric CO_2 concentrations respectively (Farquhar et al., 1982). This discrimination serves as the primary source for variability in ^{13}C values in the wholewood of *J. osteosperma*.

Chronology development

Ring widths were measured to the nearest 0.01 mm using a Leica MZ6 (x4.0) paired with a DFC 420 camera coupled with Leica Application Suit (4.1.0) software. A minimum of two transects were counted and measured for each cross-section to increase accuracy in chronologies. Crossdating accuracy was checked visually and statistically using dplR (Bunn, 2008; Bunn, 2010), and COFECA (Holmes, 1983). Measured ring width and ^{13}C series were standardized and indexed into a chronology using ARSTAN (Cook, 1985; Cook & Holmes, 1986). One tree (RC-1204) was excluded due to its significantly different signal, likely a result of being located too near the flood plain, thus representing a spring snowmelt signal and not growing season conditions like the remaining five series. All samples were detrended using the mean of each series. Since this analysis examines the 40 most modern years, any exponential curve associated with vigorous growth in the early years of a tree would not be represented, and thus the only trends seen are linear in nature.

Data from the Harmon Canyon were downloaded from the International Tree Ring Database (http://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring). The chronology is an exceptionally well dated 2,300 year *P.*

menziesii chronology from the Tavaputs Plateau (Knight et al, 2010). It has a very high mean series intercorrelation of 0.86, indicating a strong population response to climatic drivers. The moderate mean sensitivity of 0.48 is high for the species, which tends to be fairly complacent in response to climate.

Statistical analysis

A linear model was built to explore the degree of independence between ^{13}C and ring width (Fig. 2). If a high correlation existed little information could be gained from further exploration of the stable isotope chronology. Chronologies and skeleton plots were generated using dplR to remove any analysis biases. Stable isotope values were converted to positive numbers to allow seamless processing in R, thus the final ^{13}C chronology is inverted on its axis.

Principal Component Analysis (PCA) was conducted in R using the package Vegan (Oksanen et al., 2013) on a correlation matrix derived from standardized ring width and ^{13}C values. All series share a common 40 year time interval, thus none were excluded for this analysis. The resulting principal components are based on the correlation matrix.

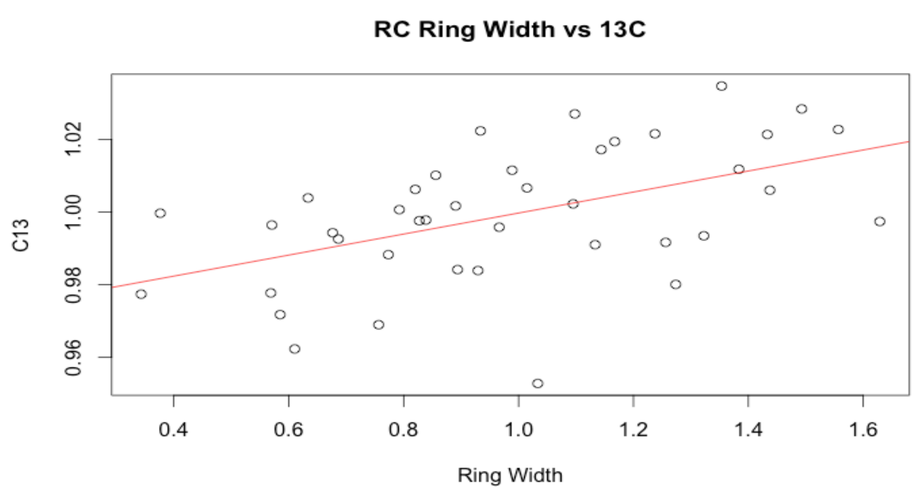

Figure 2 Linear model of 13C chronology compared to *J. osteosperma* ring width chronology

PCA is an orthogonal transformation of observations into an indexed series that aims to maximize the commonality of signal. Thus the output of the analysis is a series of new variables, or principal components, in which the total variance has been distributed as unevenly as possible. The first of these Principal Components (PC1) should be viewed as defining a model that represents the annual index that has the most common variance. The subsequent principal components (PC2, PC3, etc…) represent progressively smaller amounts of covariation within the model. While Peters et al. (1981) focused their efforts on the first principal component, this study will look to incorporate further components, with the goal of identifying time series of environmental drivers in addition to the main variation. We further explored the identified principal components for environmental responses, comparing each component to precipitation and temperature PRISM data, the Southern Oscilation Index (SOI), and the South West Monsoon Index (SWMI), in an effort to validate that these selected components represent environmental growth responses and not noise (Appendix).

CHAPTER 4

RESULTS

Linear model

Comparing the final chronology built for ring width and ^{13}C (inverted) chronology revealed a limited positive (negative) correlation with an R of .352 (p = 0.026) (Fig. 2). While some correlation between separate products of growth is expected, the limited nature of this correlation allows us to explore the possibility of semi-independent multivariate chronologies.

Ring width chronology

The moderate series intercorrelation of 0.54 indicates that extreme variations in growth are driven by a common environmental signal, but during less extreme conditions individuals express a more individual response to the environment. However, the very high mean sensitivity of 0.54 demonstrates the extreme sensitivity of the species. The skeleton plot for the ring width chronology produced a total of 10 marker years from 1973-2012, of which 8 occur during the overlapping period from the Harmon Canyon chronology (Fig. 3A).

Harmon Canyon chronology

The dplR produced skeleton plots revealed a total of 7 marker years during the 32 years, 1973-2005, that overlapped our 40 year study period (Fig. 3B).

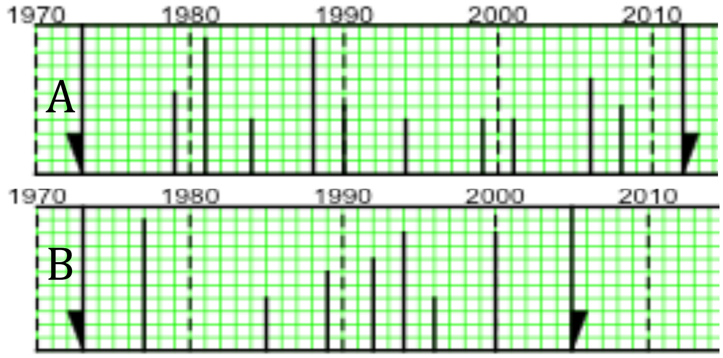

Fig. 3 Skeleton plots from: A) Range Creek *J. osteosperma* ring width; B) Harmon Canyon *P. menziesii* ring width

^{13}C Chronology

^{13}C values ranged from -23.9‰ to -19.9‰, with an average of 2.3‰ variability per series included in the chronology. A series intercorrelation of 0.27 indicates that the majority of carbon discrimination is idiosyncratic. The mean sensitivity of 0.12 shows that the amount of variation from year to year is low and represents a somewhat complacent signal. Visual comparison of each series indicates that while the response function is limited, there are several important marker years throughout the chronology. The ^{13}C chronology skeleton plot produced 9 marker years, all of which occur during the overlapping period with the Harmon chronology, and 3 of which are independent from the marker years identified in the ring width chronology (Fig. 4B). The addition of three independent marker years identified by the ^{13}C chronology over the 40 year study period increases the statistical significance of the chronology by 7.5% (Fig 4C).

PCA

The eigenvalues from the principal component analysis show that the first three components meet the criteria for the Kaiser rule (Bandalos & Boehm-Kaufman, 2008), with each accounting for more than 10% of the total explained variance (Table 1, Fig. 5). While much of the power of a PCA lies in the ability to identify underlying signals and trends, and not necessarily in marker years as traditionally understood in the

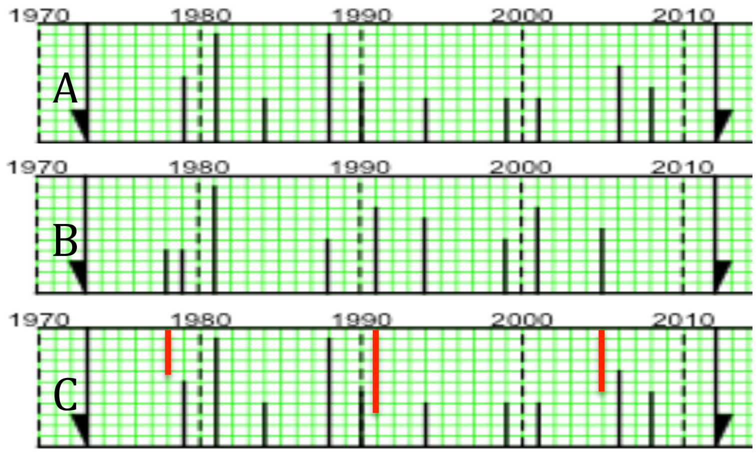

Fig. 4 Chronology intercomparison: A) Ring width; B) 13C; C) combined multivariate, where independent marker years are identified as red bars originating from the top of graph

Table 1 PCA Results

	PC1	PC2	PC3	Total
Eigenvalue	3.4593	1.8689	1.2275	6.557
Marker Years	8	9	10	27
Independent Markers		7	7	14

dendrochronological community, we produce skeleton plots for each eigenvalue to demonstrate the sensitivity of each of the three environmental signals captured, and look at how years of significant change are represented (Fig. 6). PC1 identified 8 marker years, while PC2 and PC3 identified 9 and 10 respectively, all with different timing of when these years occurred.

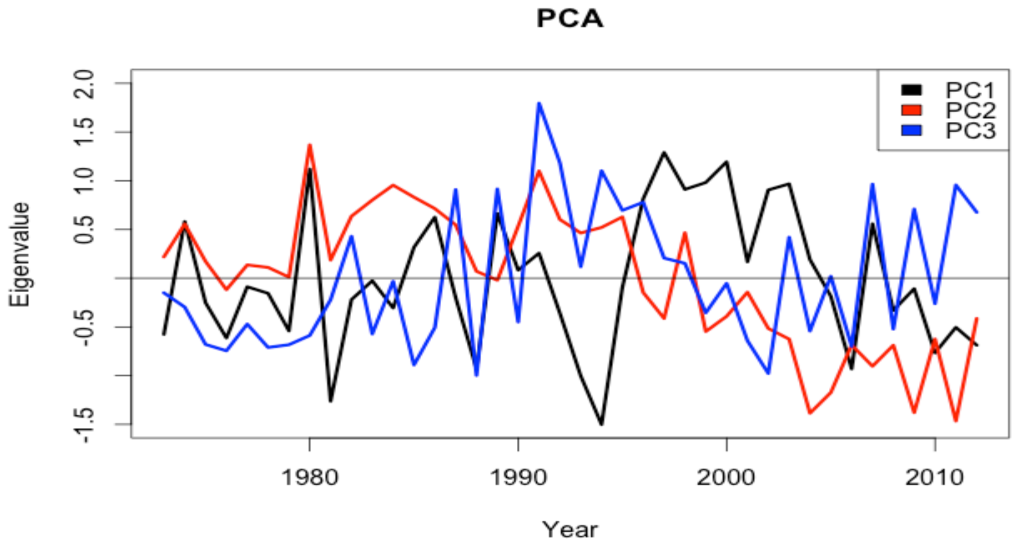

Fig. 5 PCA time series

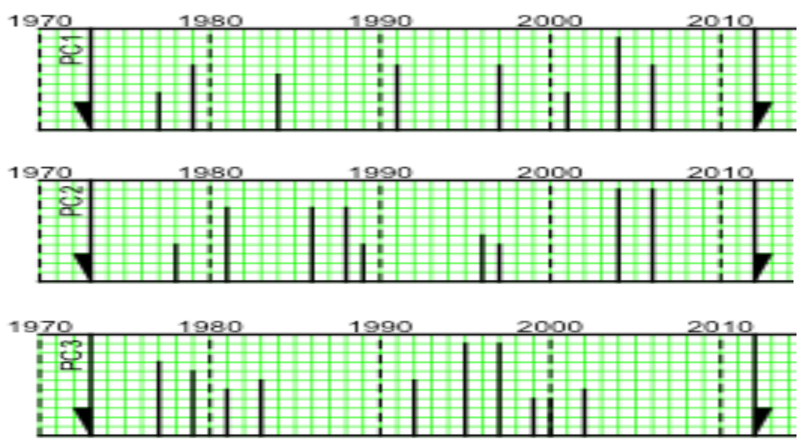

Fig. 6 Skeleton plots for PC1, PC2, and PC3

CHAPTER 5

DISCUSSION

The failure to successfully crossdate dendrochronological materials can be the result of several limiting factors. As described by Towner et al., (2009) the species, the size of material, the number of rings, and the sensitivity of the master chronology all impact crossdating success. Since we cannot control the species or size of the available material, particularly with archeological samples, increasing the sensitivity of the master chronology is the best method by which to increase crossdating success.

In order to address the questions raised at the outset of the study, we compared our results to the Harmon chronology (Fig. 3). This is purely an exercise in exploring the increased sensitivity of our chronology. Differences in chronology development, species, site, and possible problems resulting from missing or false rings may result in a higher measure of difference. Thus the total number of marker years in a given period may be a better measure of significance than trying to match independent years from one chronology to another.

The first question asked whether the use of a more sensitive species results in an increased number of identified marker years over the Harmon Canyon chronology, we compared the *J. osteosperma* ring width to the most recent 32 years of the Harmon Canyon chronology (Fig. 3).

The *J. osteosperma* ring width chronology identified one additional marker year compared to the Harmon Canyon *P. menziesii* chronology. This represents a 3.125% increase in the statistical significance of the chronology. This increase is fairly insignificant considering the extra difficulty in developing a chronology using *J. osteosperma*.

To address question two, does the addition of the second variable increase the statistical significance of the chronology by identifying additional independent marker years, we compared the ^{13}C and the combined multivariate chronology to the most recent 32 years of the Harmon Canyon chronology.

The ^{13}C chronology identified 3 independent marker years, increasing the number of marker years in the chronology by 9.375% compared to Harmon Canyon chronology. After combining the *J. osteosperma* ring width chronology with the ^{13}C chronology, the resulting combined multivariate chronology identified an additional 4 marker years during the 32 year overlapping period, or a 12.5% increase in the overall sensitivity.

Since the majority of this increase (75%) came from the addition of the ^{13}C chronology, and not from the use of a more sensitive species, the minimal gain in signal from using a more sensitive species may not be worth the time required to produce a reliable chronology from such a problematic species. Further, preliminary results from a *P. menziesii* chronology from Bryce Canyon, Utah (Ehleringer et al., unpublished data) suggest a similar increase in signal from the addition of ^{13}C as well as other isotope chronologies. Thus the addition of semi-indipendent chronologies to a more dendrochronologically reliable species may be more beneficial than the use of a sensitive species.

Regarding the third question, if the resulting multivariate chronology could be used to identify additional indexes by which more advanced crossdating methods could be applied, our PCA revealed three statistically significant underlying indexes (PC1, PC2 and PC3) (Fig. 5). Further, each additional index showed a different structure in the occurrence of marker years, compared to the first component. Both PC2 and PC3 identified 7 marker years that were independent from PC1, resulting in a 17.5% increase in significance with the addition of either index (Table 1). Since the majority of the marker years identified in PC2 are independent from PC3, and all the retained components are assumed to contain environmental signals, the use of all three indexes provides a wealth of potential signals to crossdate against.

These alternative indexes could be used to match problematic series that may be responding to different environmental drivers, and so exhibit slightly different responses than the dominant population signal. Our investigation of potential responses between our principal component indexes and environmental signals revealed that PC1 responds primarily to precipitation (Table 2, Fig. 7), PC2 has a strong response to temperature

Table 2 PC Response Coefficients

	PC1std	PC2std	PC3std	SOI	SWMI	Temp	Precip
PC1std	1	-0.01038	0.004468	0.074818	0.168494	0.071327	0.118718
PC2std	-0.01038	1	0.010588	-0.22674	0.003152	0.520097	0.151882
PC3std	0.004468	0.010588	1	-0.10896	0.101115	-0.13664	-0.30879
SOI	0.074818	-0.22674	-0.10896	1	-0.41445	-0.0246	-0.27938
SWMI	0.168494	0.003152	0.101115	-0.41445	1	-0.29274	0.489308
Temp	0.071327	0.520097	-0.13664	-0.0246	-0.29274	1	0.088299
Precip	0.118718	0.151882	-0.30879	-0.27938	0.489308	0.088299	1

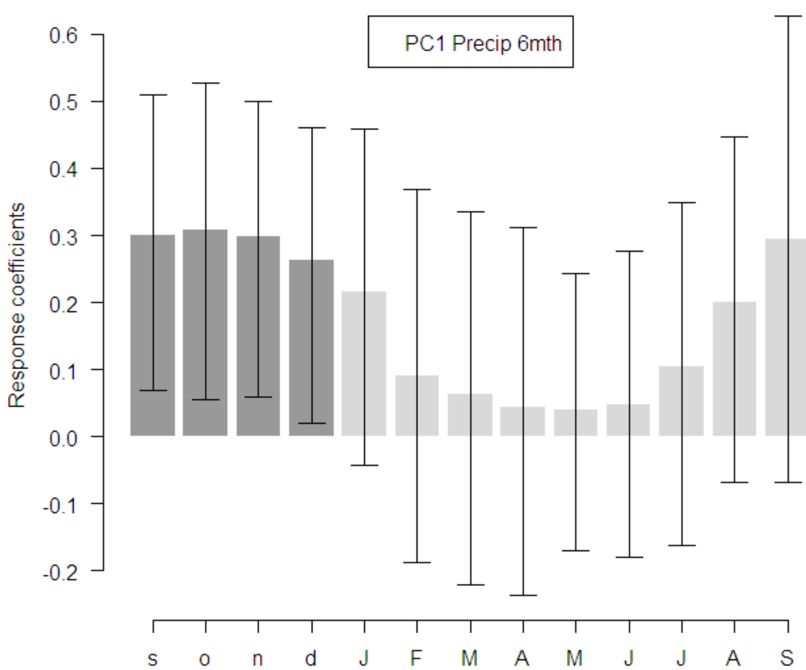

Figure 7 PC1 six month precipitation response coefficient

(Table 2, Fig. 8), and PC3 responds negatively to both precipitation and temperature (Table 2, Fig. 9 and Fig. 10). These responses suggest that all three selected principal component indexes are environmentally driven, and not organized noise.

Care must be taken when considering how to implement these additional indexes. The consolidation of each independent marker from all principal components into a synthetic chronology, as done with our ^{13}C multivariate chronology, would result in a master skeleton plot with a very high number of marker years, but as these are derived from three different environment/growth responses, it would be impossible to match a single series (and response). Instead, each principal component index should be treated as an alternative chronology to compare unmatched series to during the crossdating process, providing crossdating targets for individual series that may have different environmental responses to the population response. Any additional semi-independent variable, such as ^{18}O or ^{2}H values, could easily be added to the PCA allowing for the identification of more indexes.

Further, PCA allows for the full signal, including trends, to be used in matching segments, rather than relying solely on the visual comparison of extreme deviations of one variable. This could easily be accomplished by implementing a dissimilarity metric (Randic et al., 2003).

Based on our findings, we recommend that a multivariate chronology be developed for the entirety of Range Creek occupation through the present, using a more dendrochronologically reliable species like *P. menziesii*. Additionally, the availability of the Harmon Canyon chronology makes *P. menziesii* ideal for this project. When particular unknown series do not appear to match the dominant signal, and thus cannot be matched to the resulting multivariate master chronology, we suggest implementing the PCA signal matching technique explored above.

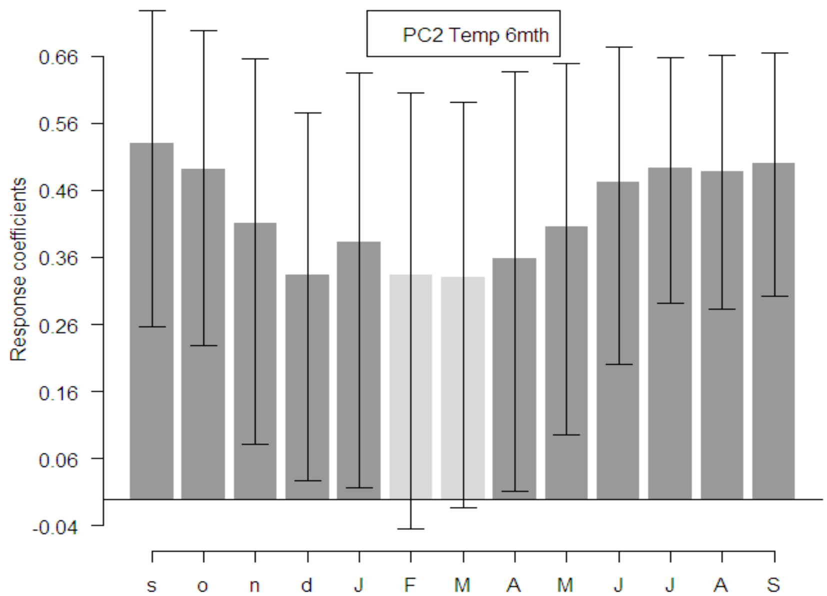

Figure 8 PC2 average temperature six month grouped response coefficient

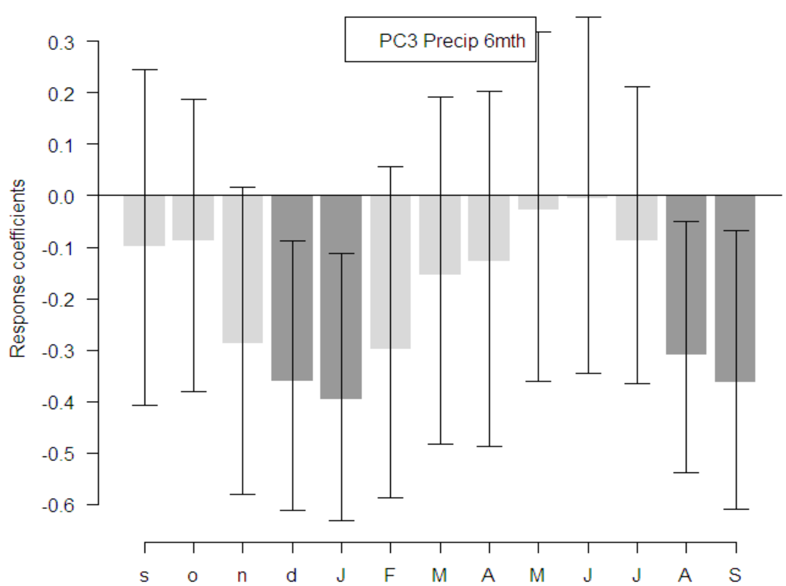

Figure 9 PC3 precipitation six month grouped response coefficient

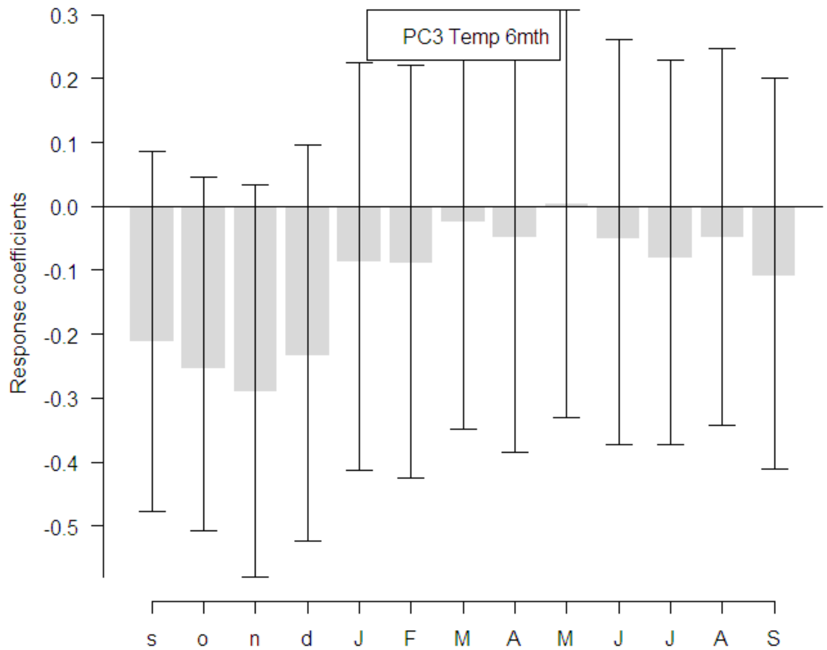

Figure 10 PC3 average temperature six month grouped response coefficient

CHAPTER 6

CONCLUSION

Our results demonstrate that: 1) the increase in the statistical significance of a chronology due to the use of a more sensitive species over a traditionally dendrochronologically reliable one is limited, and is likely not worth the additional effort, unless the alternative source is highly complacent. 2) The addition of a second variable, ^{13}C in this instance, resulted in a significant increase in the sensitivity of the chronology. 3) The addition of a second variable allows for the identification of additional indexes that could be used in the crossdating process.

The cost, both in terms of time and financial investment, should be taken into consideration when contemplating the development of a multivariate chronology. If crossdating is fairly successful when relying on a ring width index and visual matching of extreme events represented in skeleton plots, then the extra time and cost is probably not necessary. If, however, success rates of crossdating are limited, the addition of the second chronology in a visual platform may yield higher rates of success. Finally, if the addition of the second variable still yields limited success, the exploration of alternative matching methods, such as the PCA performed in this study, may result in even higher rates of successfully placing undated series.

The use of multivariate chronologies has great potential to increase the statistical sensitivity of any master chronology, which in turn greatly enhances the ability to accurately crossdate dendroarcheological materials. Potentially the greatest advantage of a multivariate chronology is the ability to go further in exploring the underlying structure and signal of the data and extract multiple environmental signals controlling tree growth. The use of PCA as a potential method for crossdating offers a powerful new way to approach crossdating that will allow a shift away from a visual, single variable method to a multivariate structural and statistical approach. While our analysis stopped short of this step, the addition of a multivariate chronology allows for the beginning of this discussion.

APPENDIX

RESPONSE FUNCTIONS

Table 3 Response Coefficients

	PC1std	PC2std	PC3std	SOI	SWMI	Temp	Precip
PC1std	1	-0.01038	0.004468	0.074818	0.168494	0.071327	0.118718
PC2std	-0.01038	1	0.010588	-0.22674	0.003152	0.520097	0.151882
PC3std	0.004468	0.010588	1	-0.10896	0.101115	-0.13664	-0.30879
SOI	0.074818	-0.22674	-0.10896	1	-0.41445	-0.0246	-0.27938
SWMI	0.168494	0.003152	0.101115	-0.41445	1	-0.29274	0.489308
Temp	0.071327	0.520097	-0.13664	-0.0246	-0.29274	1	0.088299
Precip	0.118718	0.151882	-0.30879	-0.27938	0.489308	0.088299	1

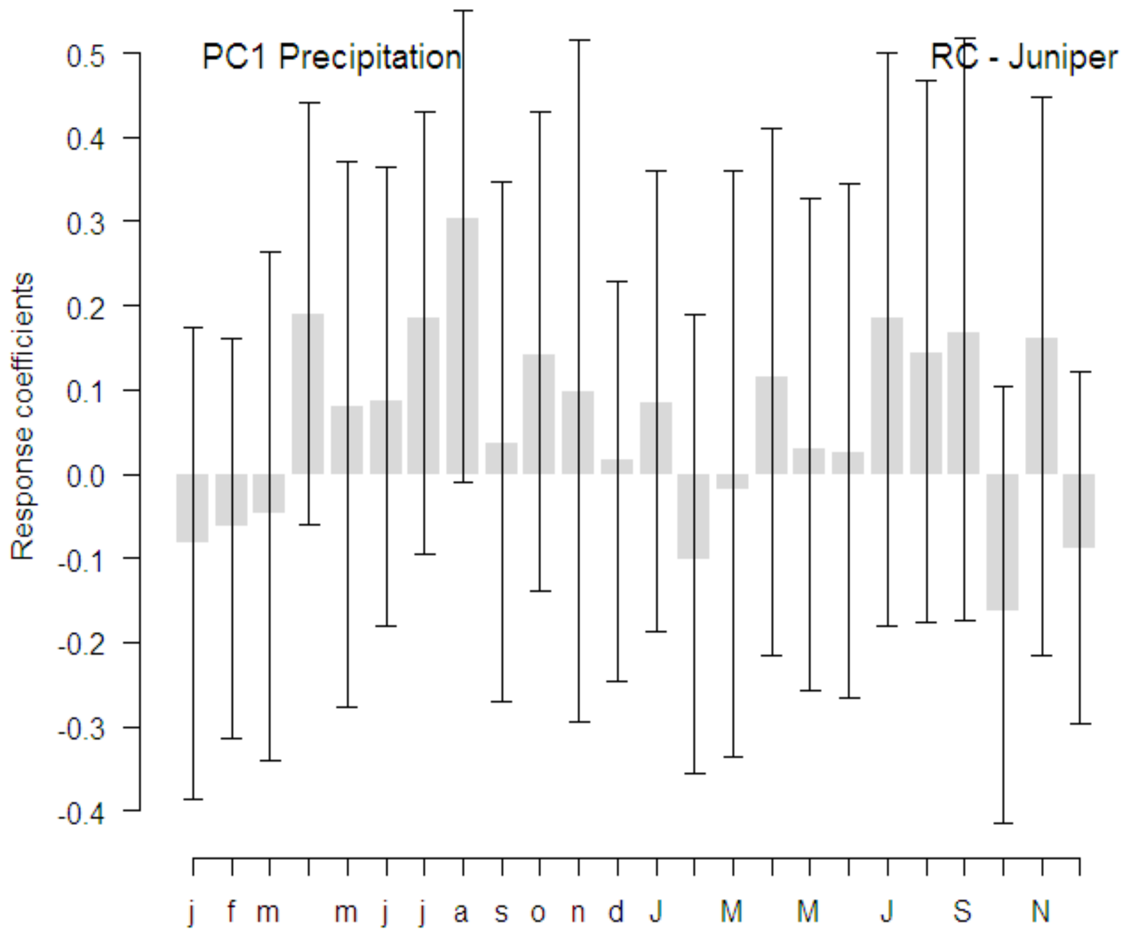

Figure 11 PC1 monthly precipitation response coefficient

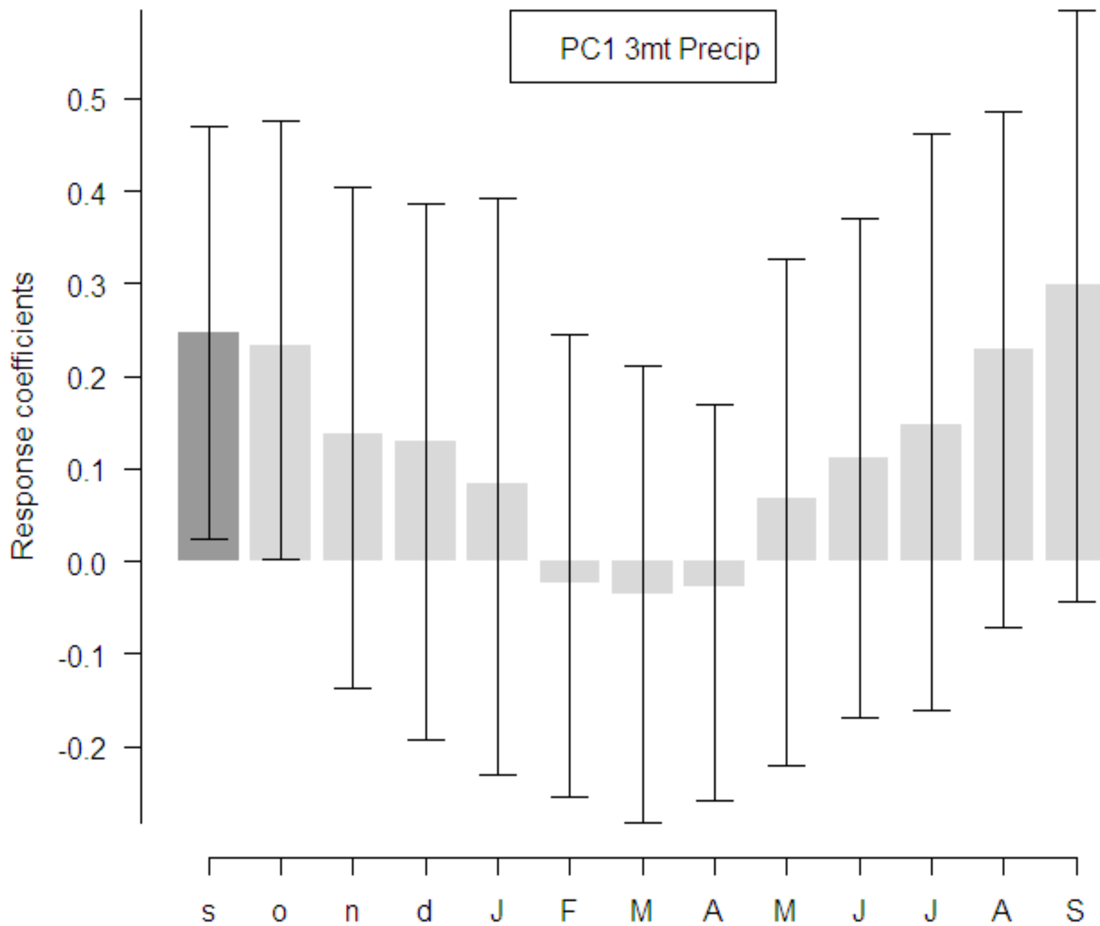

Figure 12 PC1 three month binned precipitation response coefficient

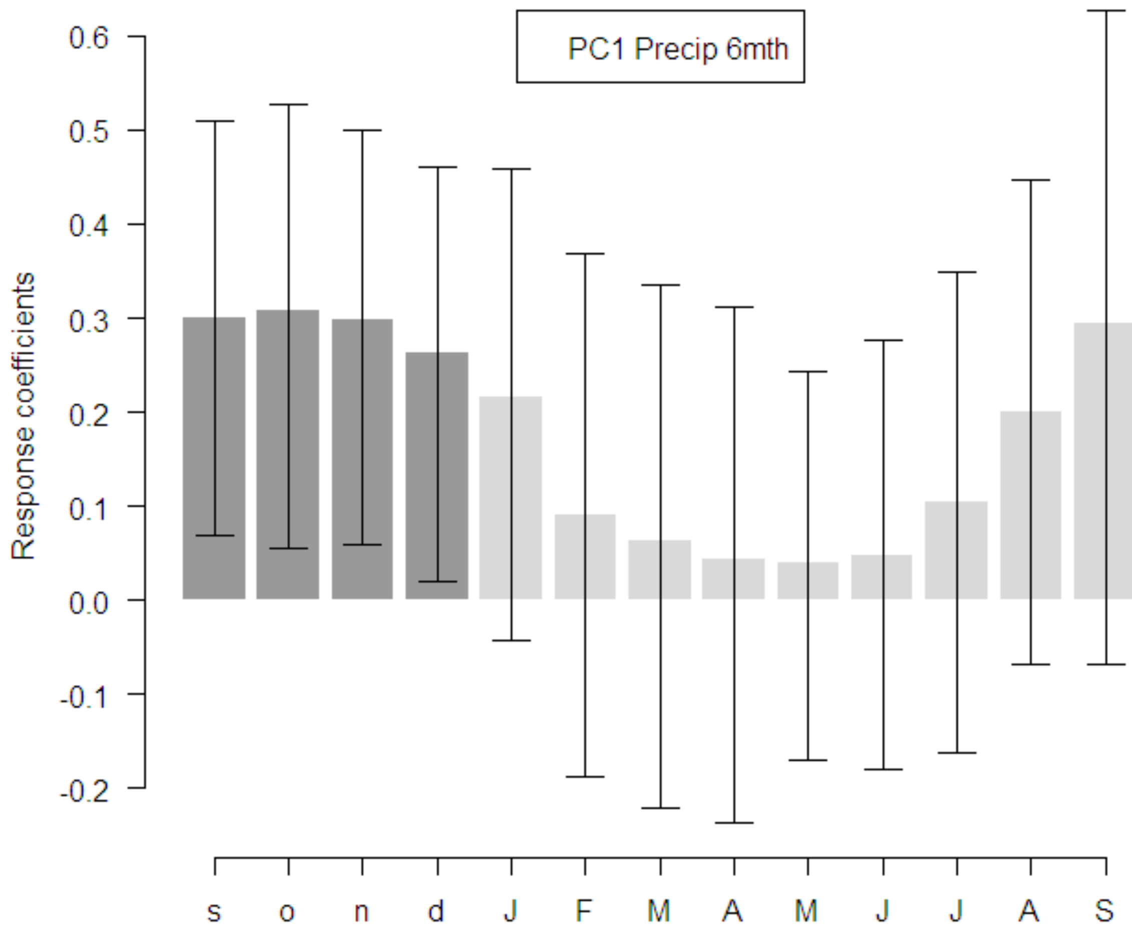

Figure 13 PC1 six month precipitation response coefficient

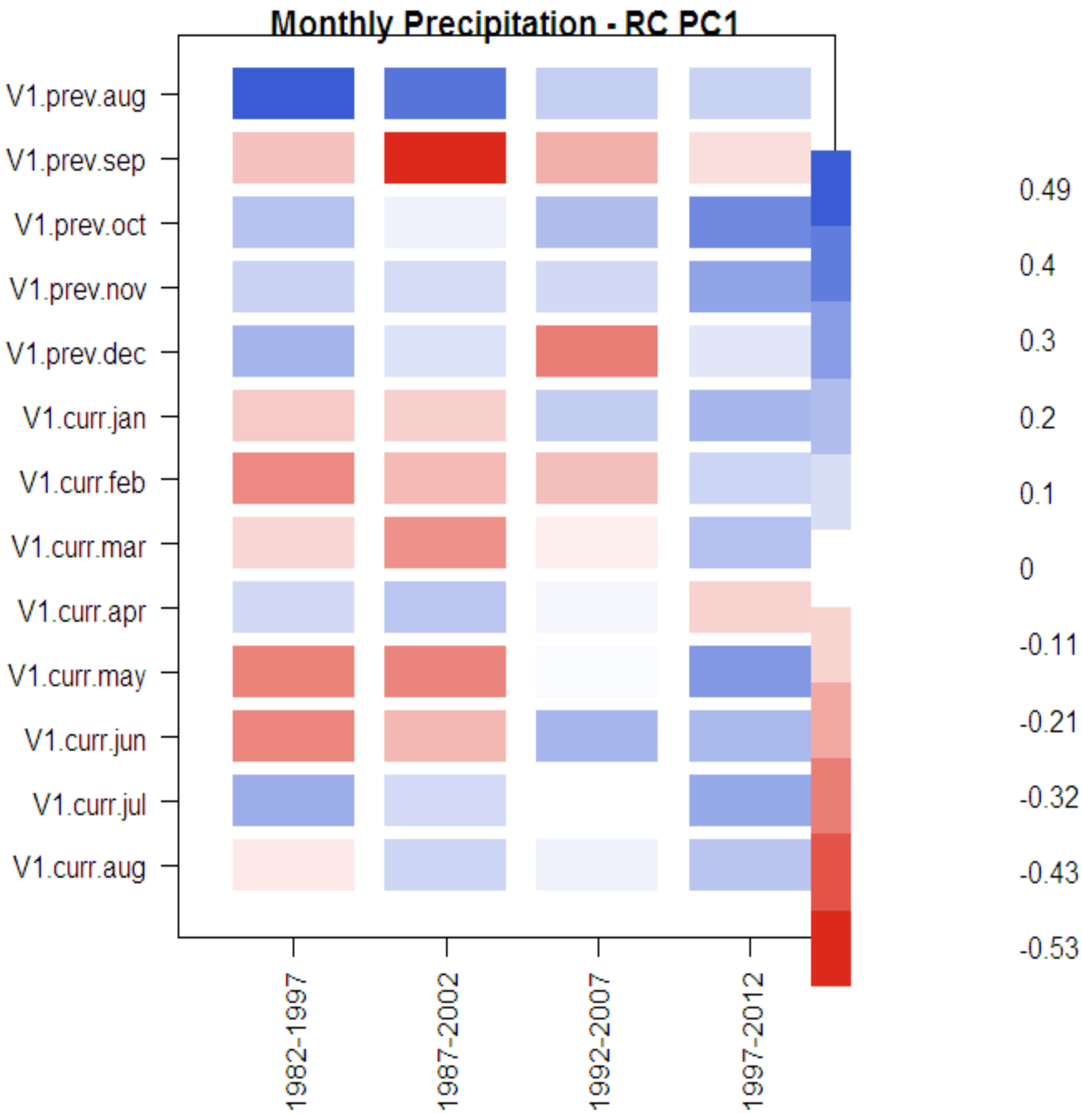

Figure 14 PC1 monthly precipitation response coefficient over time

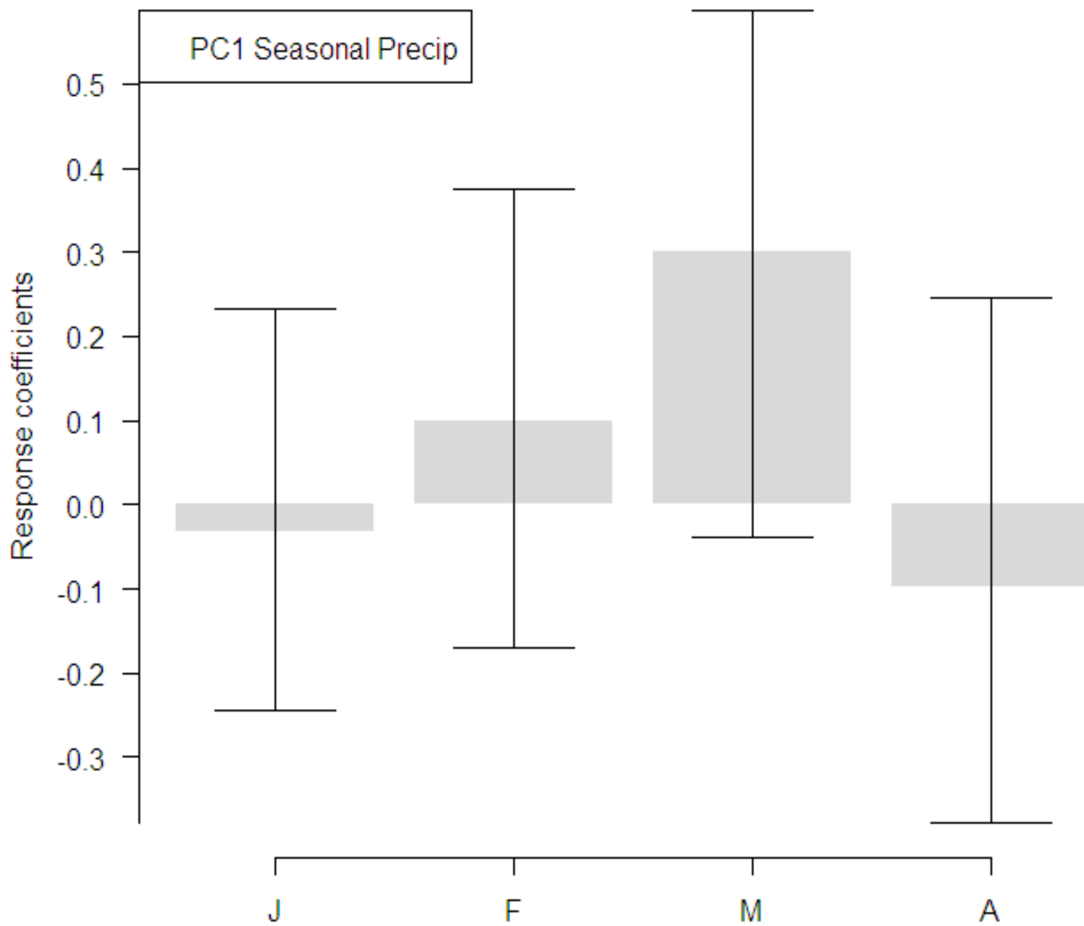

Figure 15 PC1 seasonally grouped precipitation response coefficient

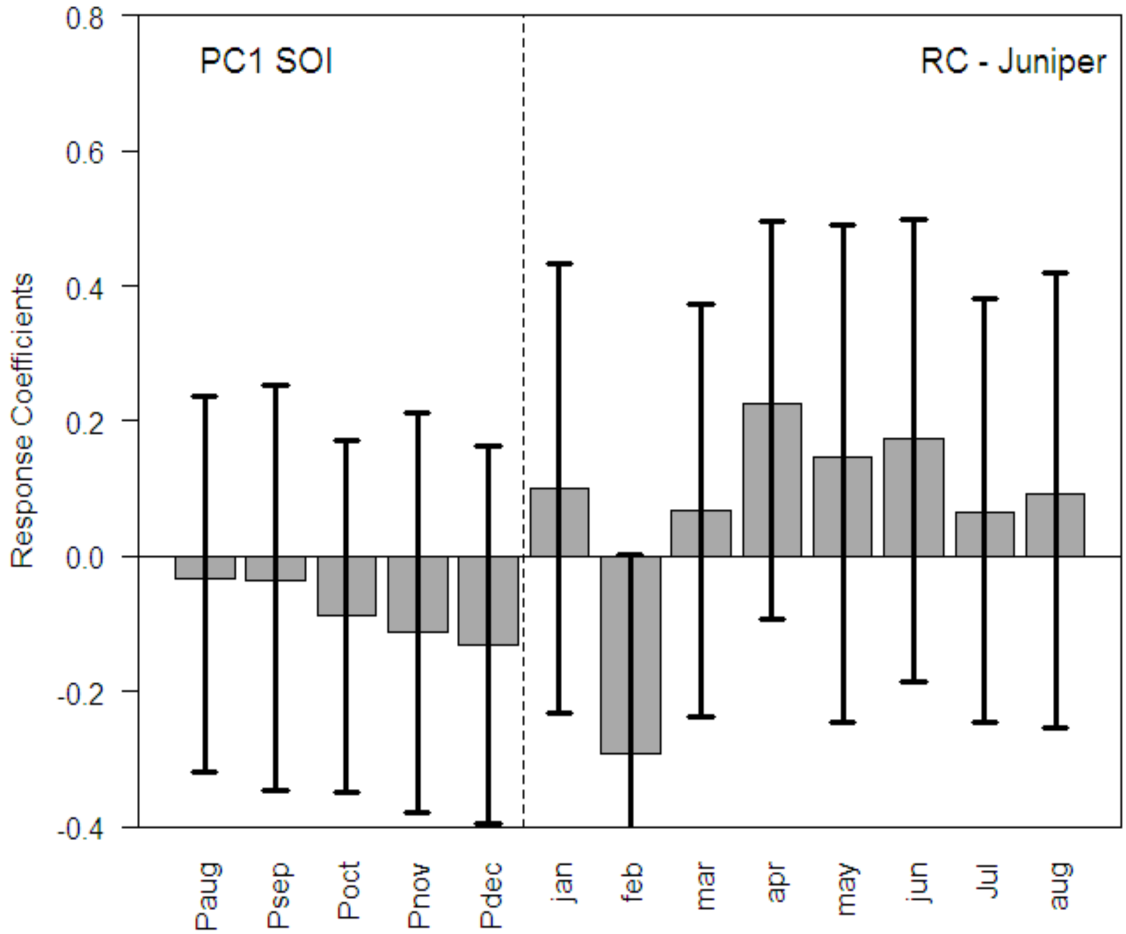

Figure 16 PC1 southern oscillation index monthly response coefficient

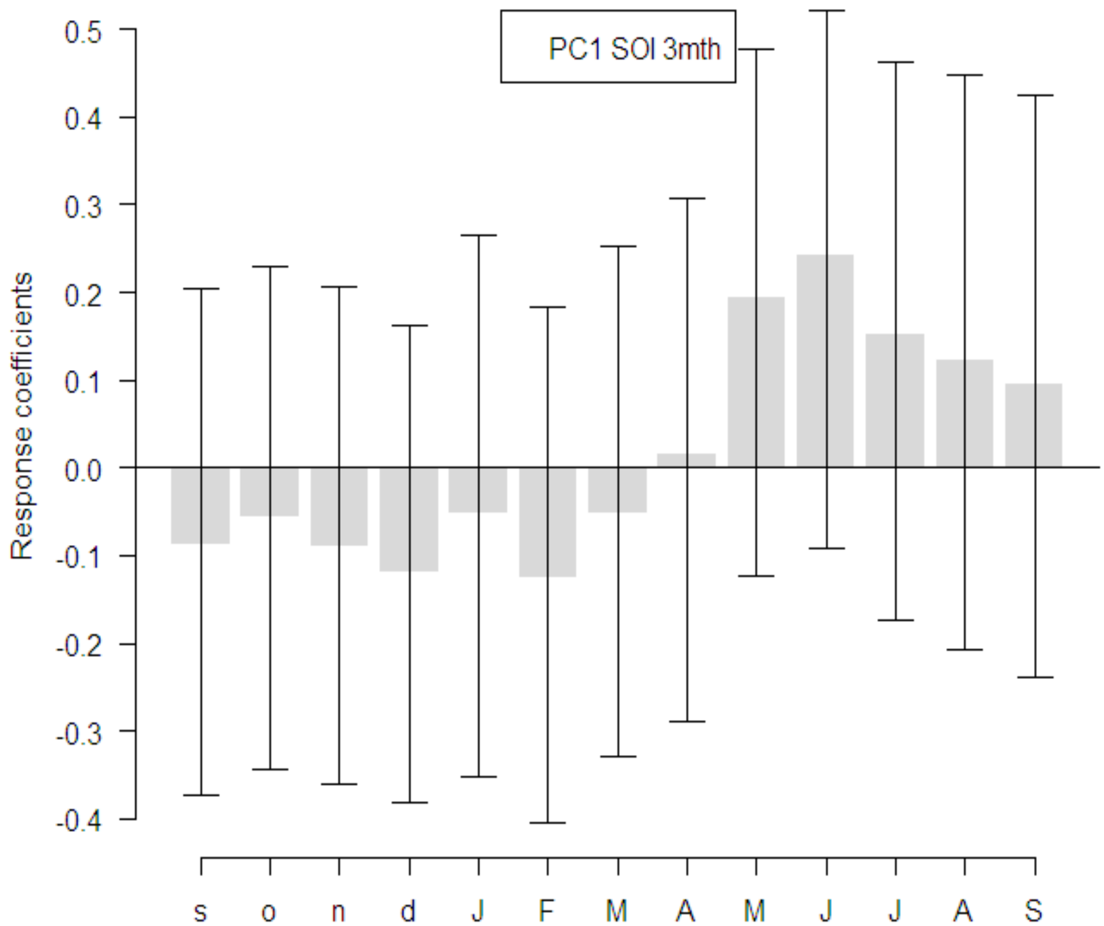

Figure 17 PC1 southern oscillation index three month grouped response coefficient

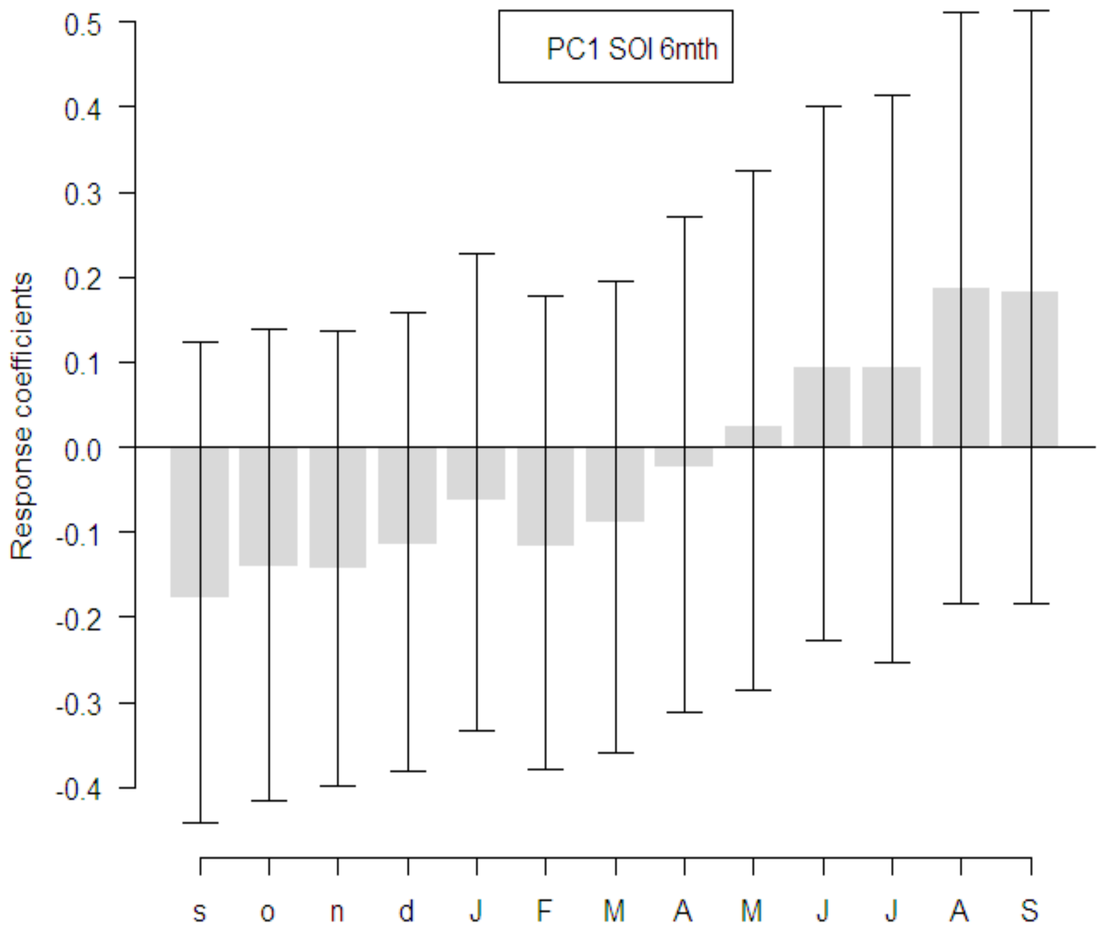

Figure 18 PC1 southern oscillation index six month grouped response coefficient

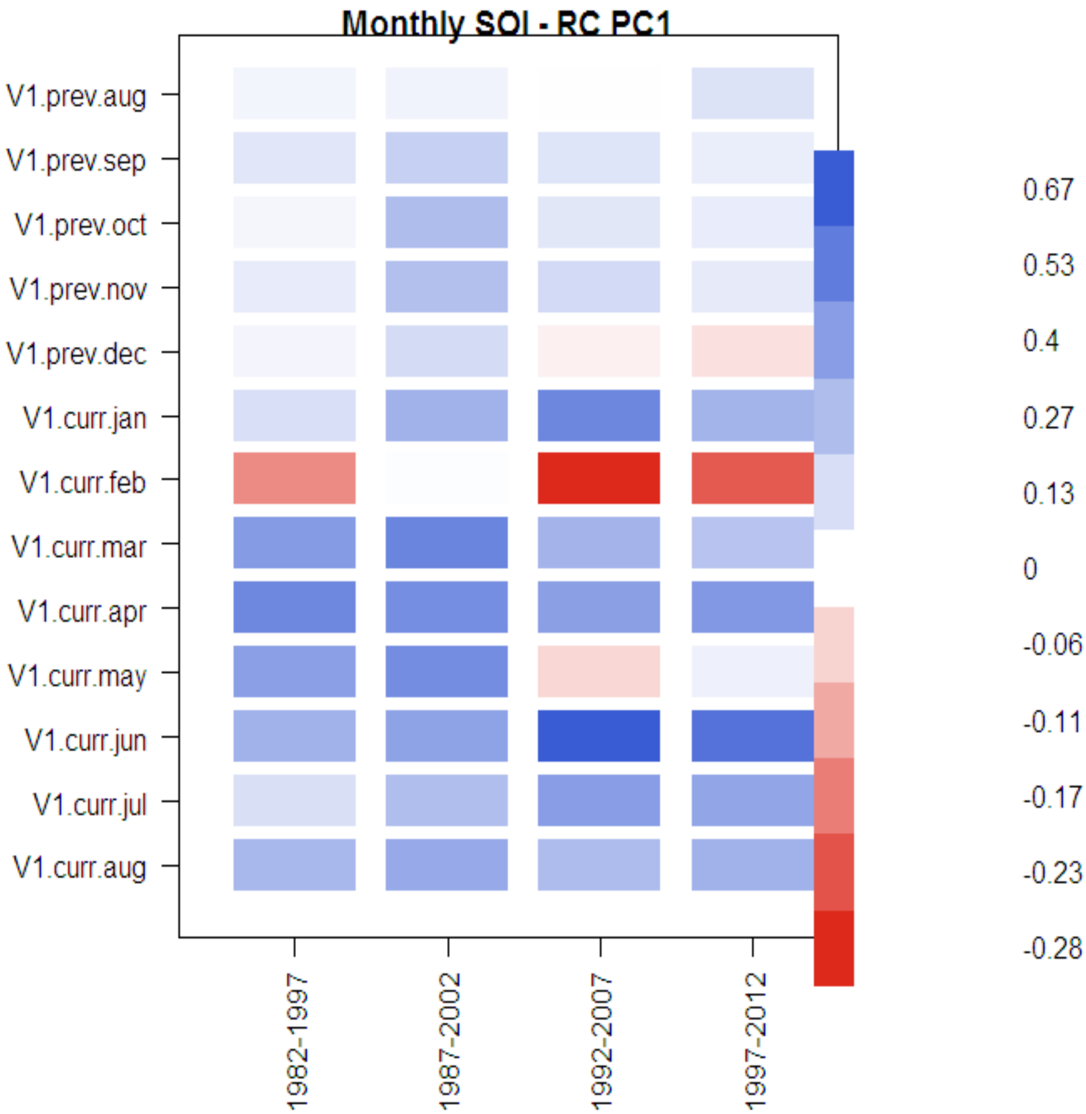

Figure 19 PC1 southern oscillation index monthly response coefficient over time

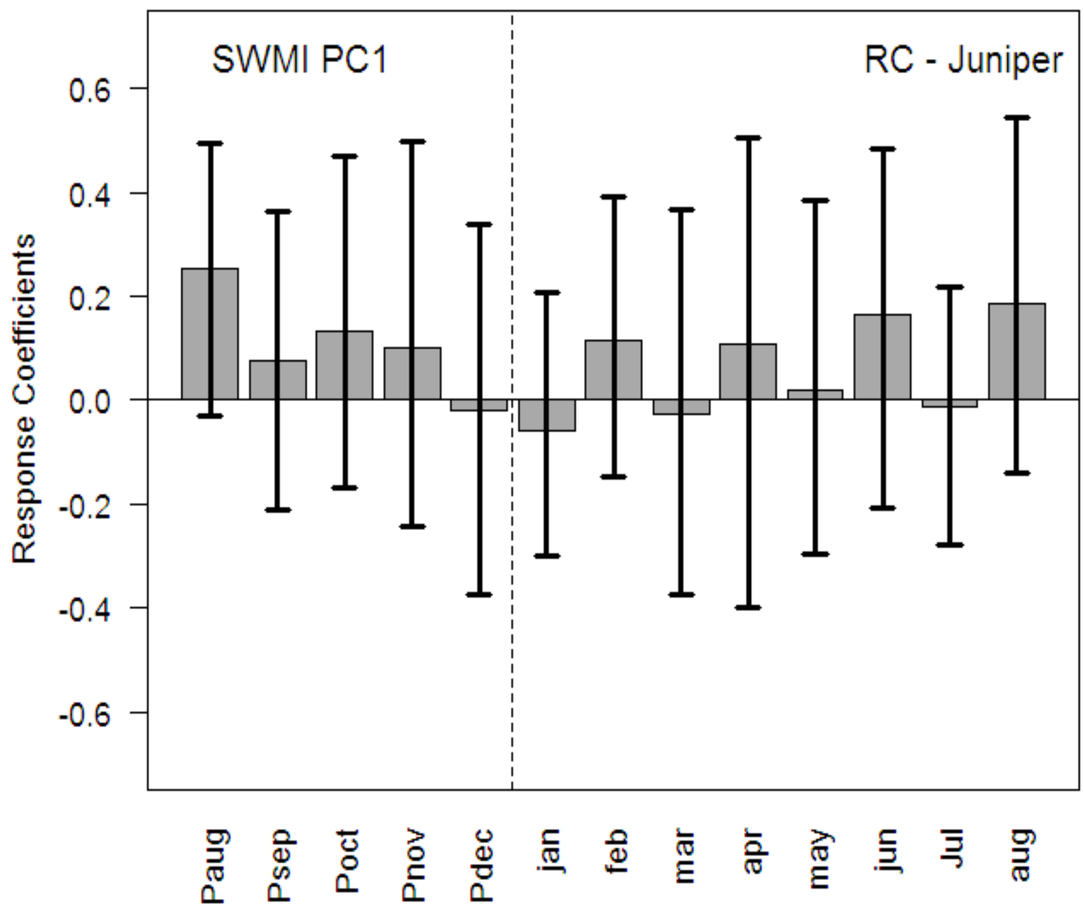

Figure 20 PC1 southwest monsoon index monthly response coefficient

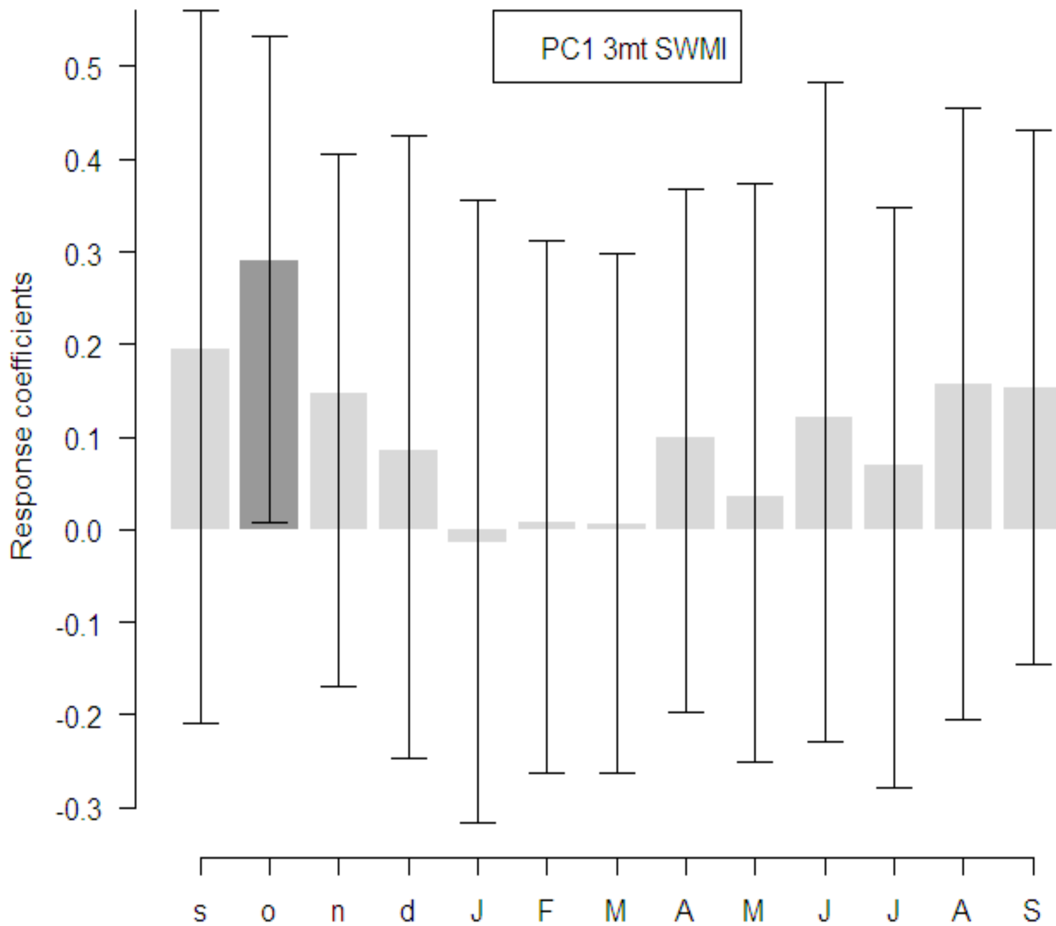

Figure 21 PC1 southwest monsoon index three month response coefficient

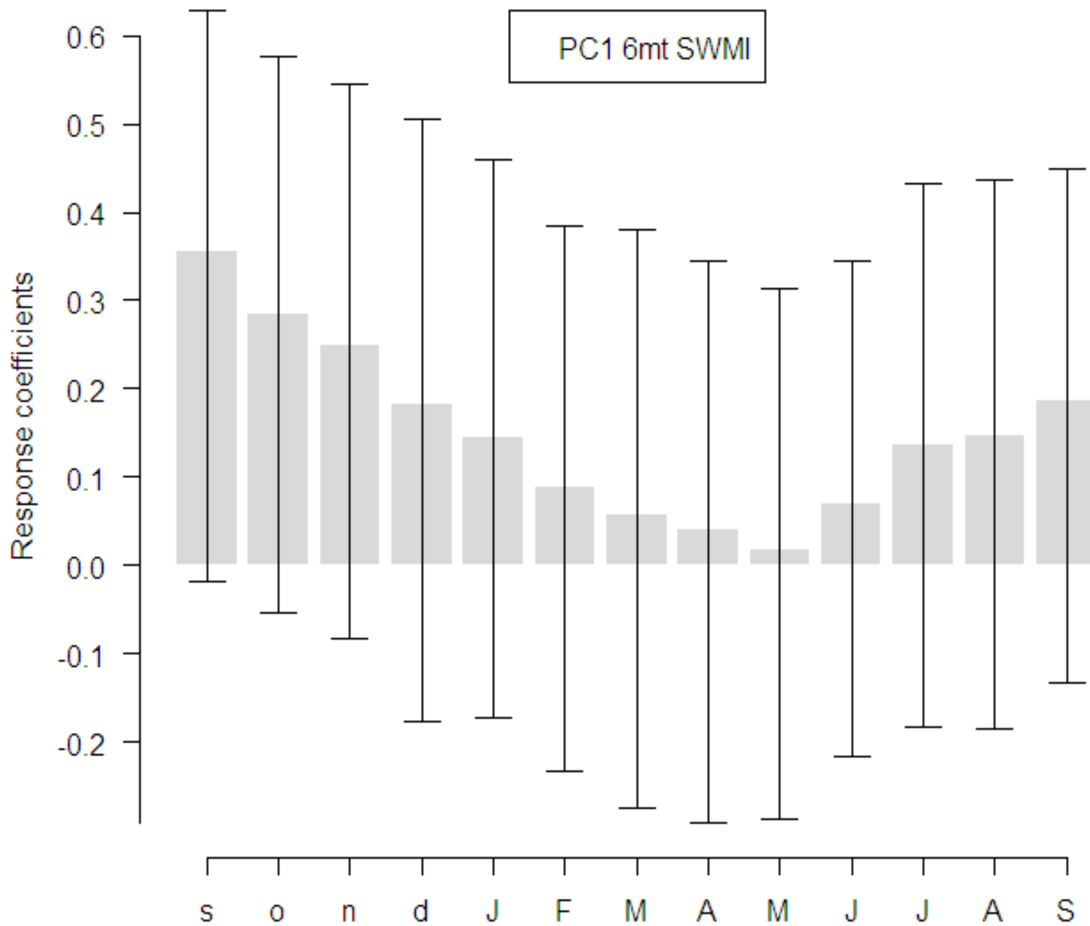

Figure 22 PC1 southwest monsoon index six month grouped response coefficient

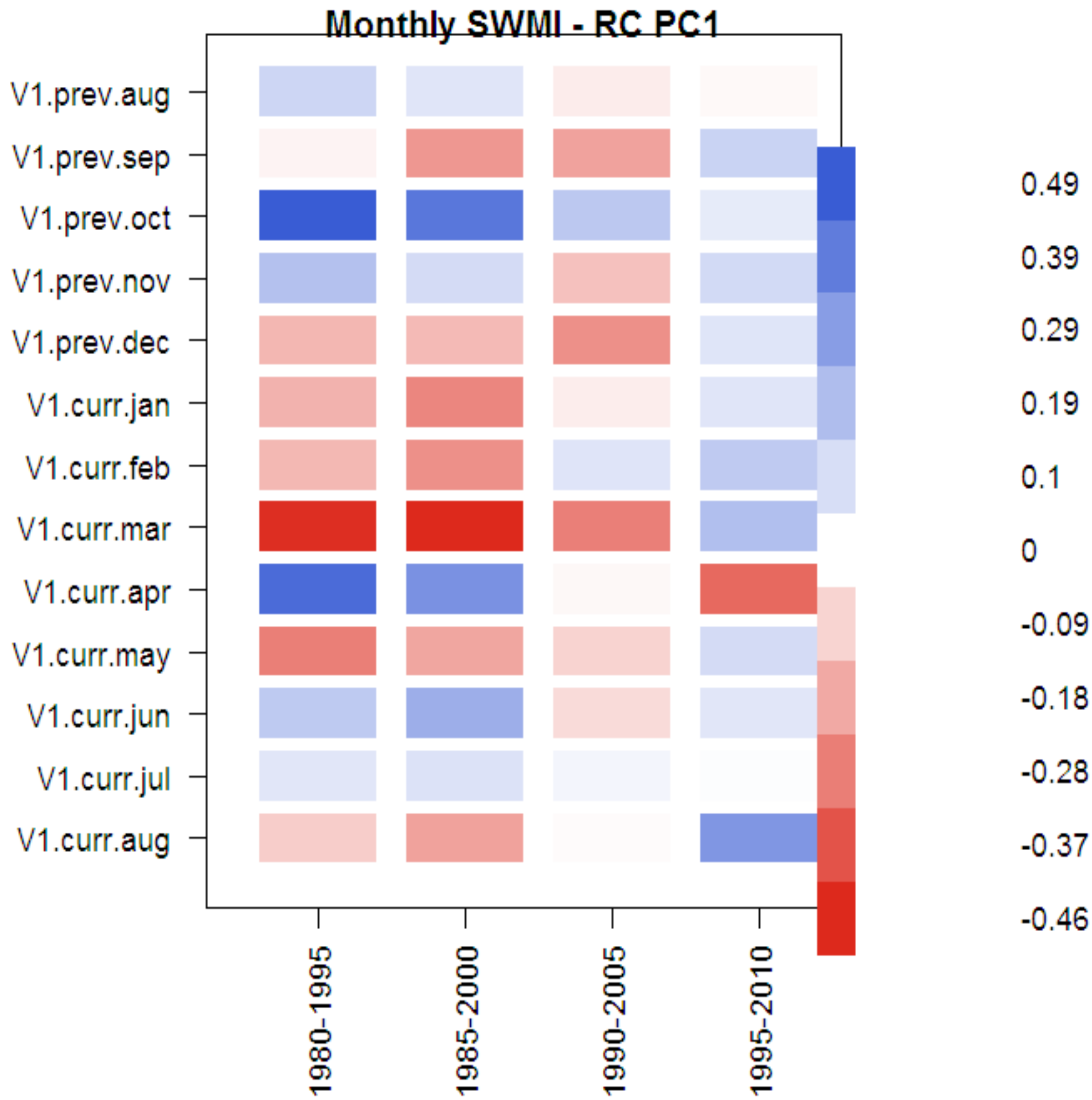

Figure 23 PC1 southwest monsoon index monthly response coefficient over time

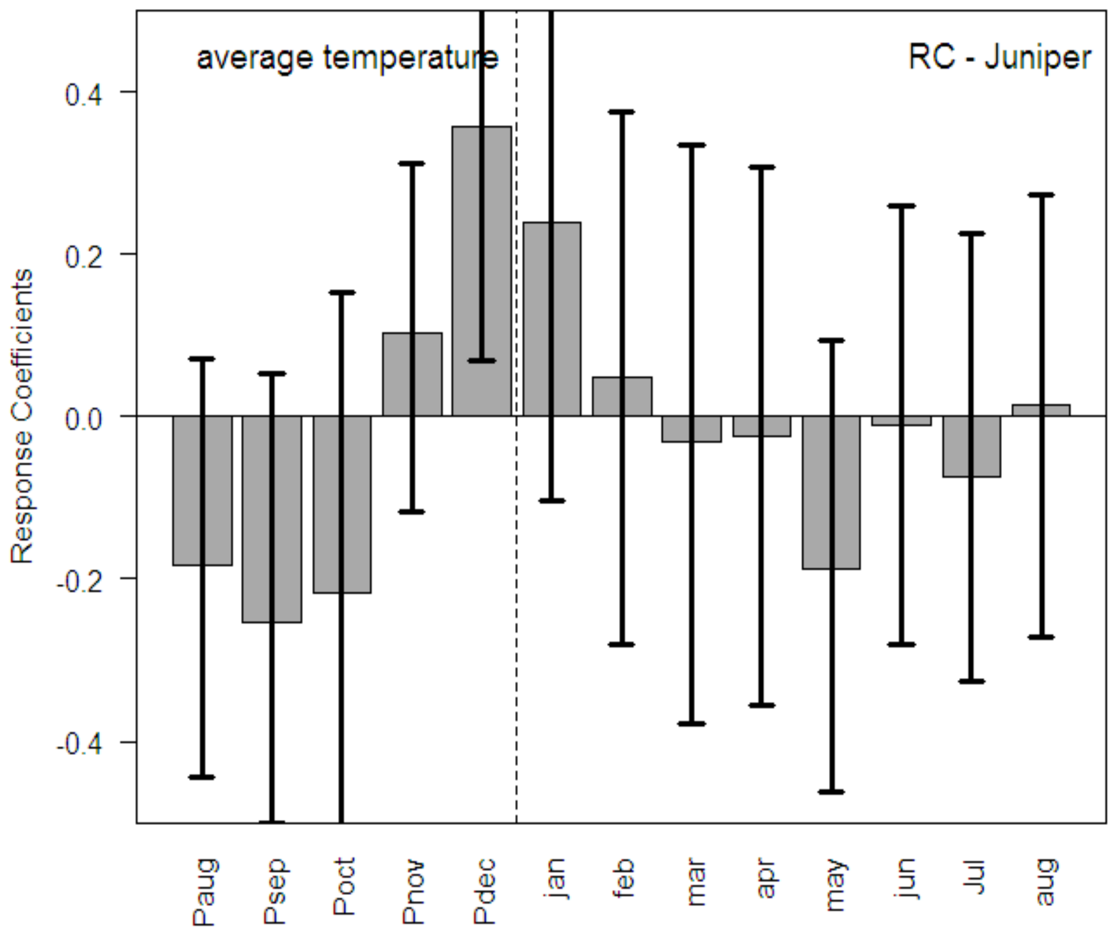

Figure 24 PC1 average temperature monthly response coefficient

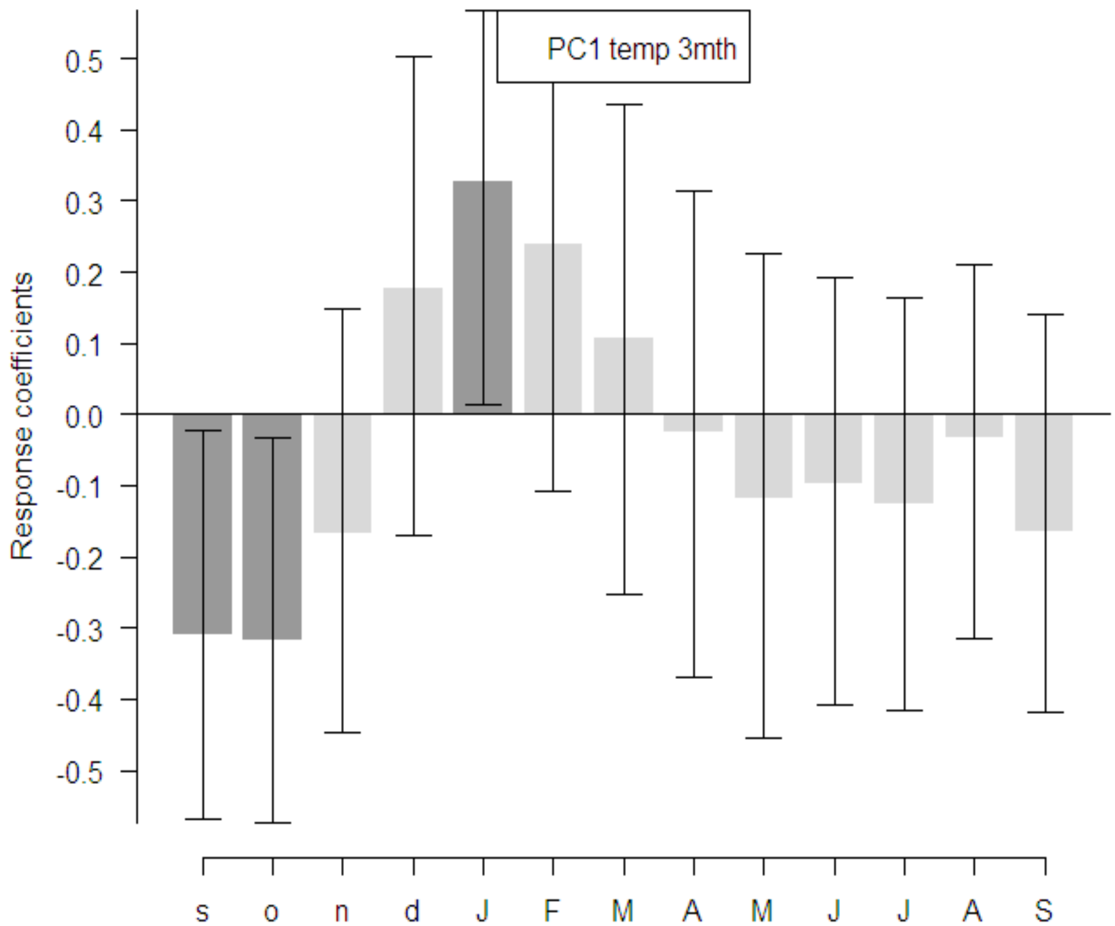

Figure 25 PC1 average temperature three month grouped response coefficient

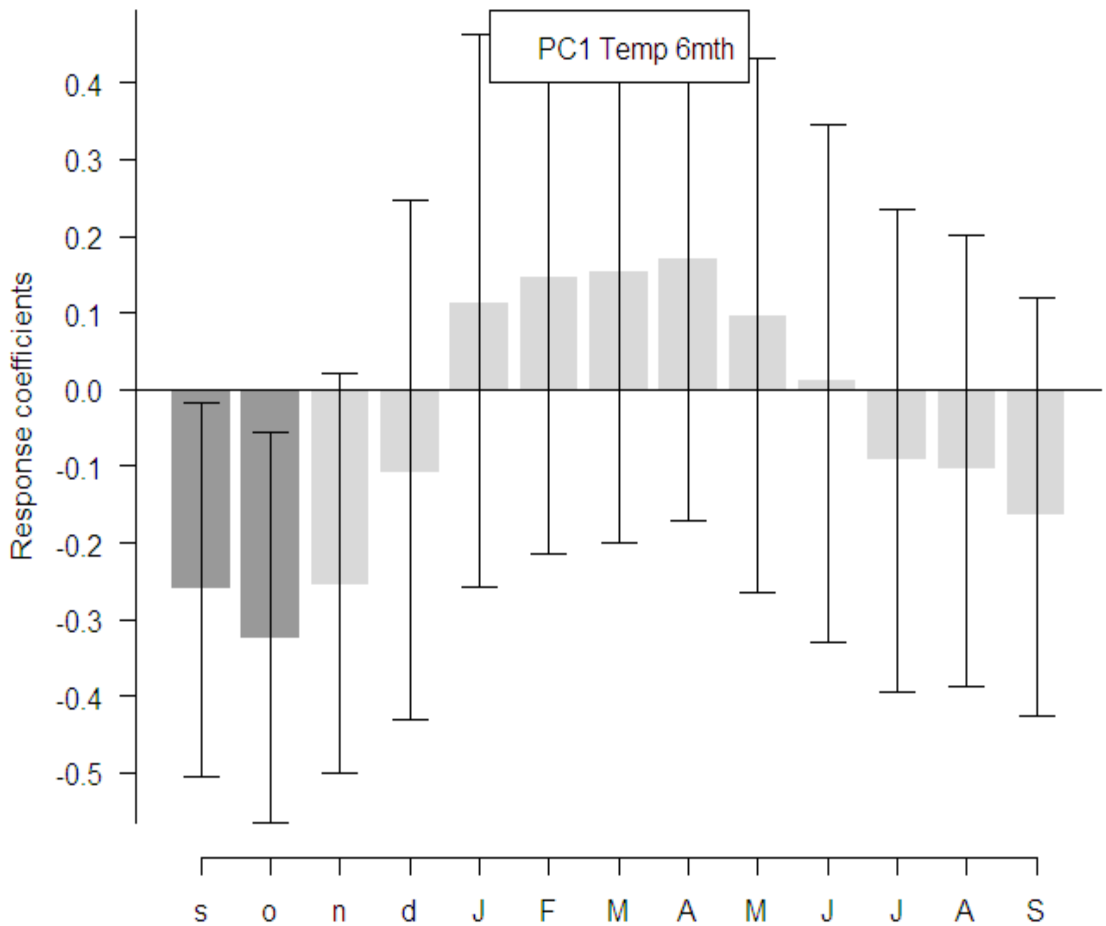

Figure 26 PC1 average temperature six month grouped response coefficient

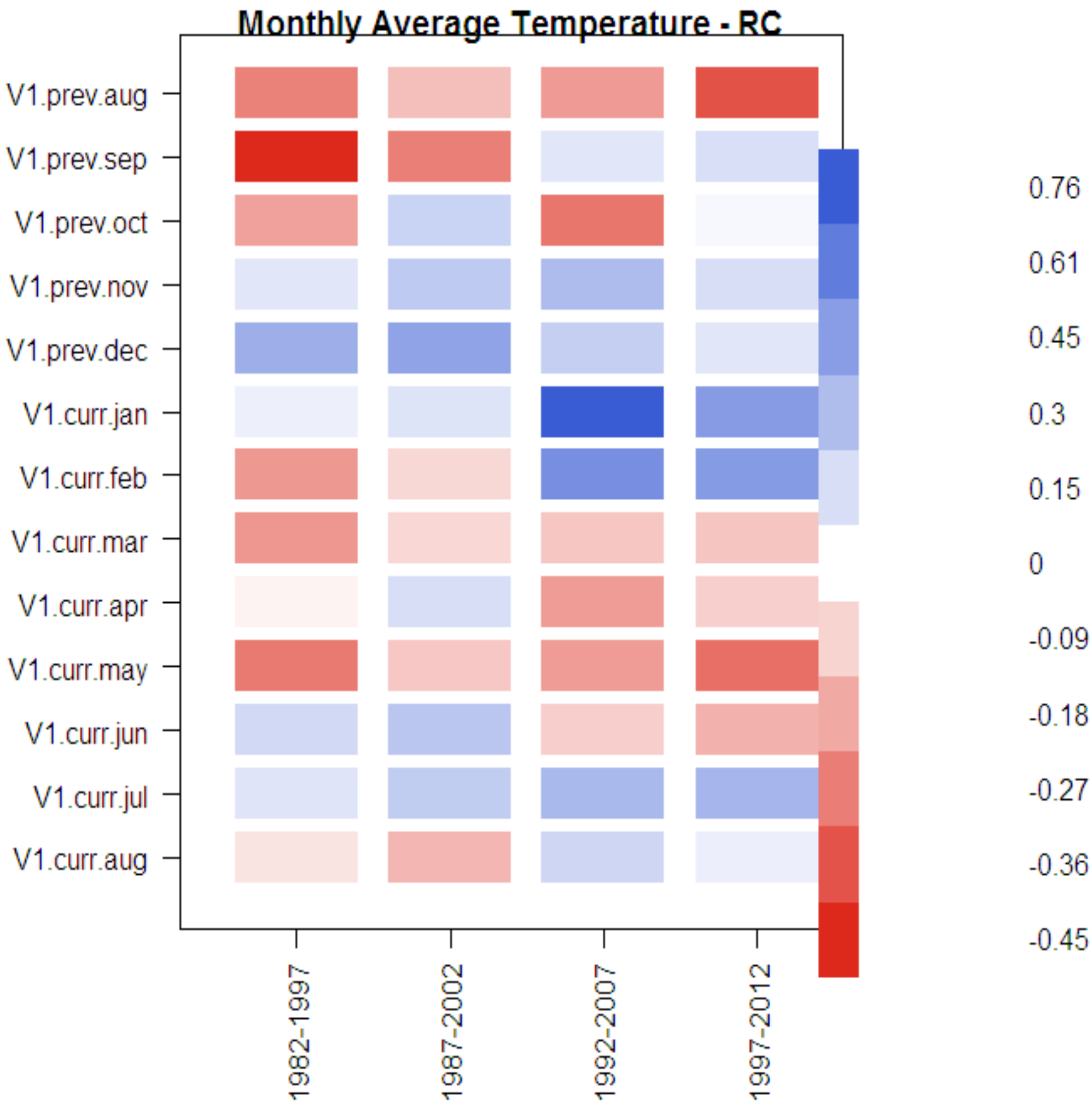

Figure 27 PC1 average temperature monthly response coefficient over time

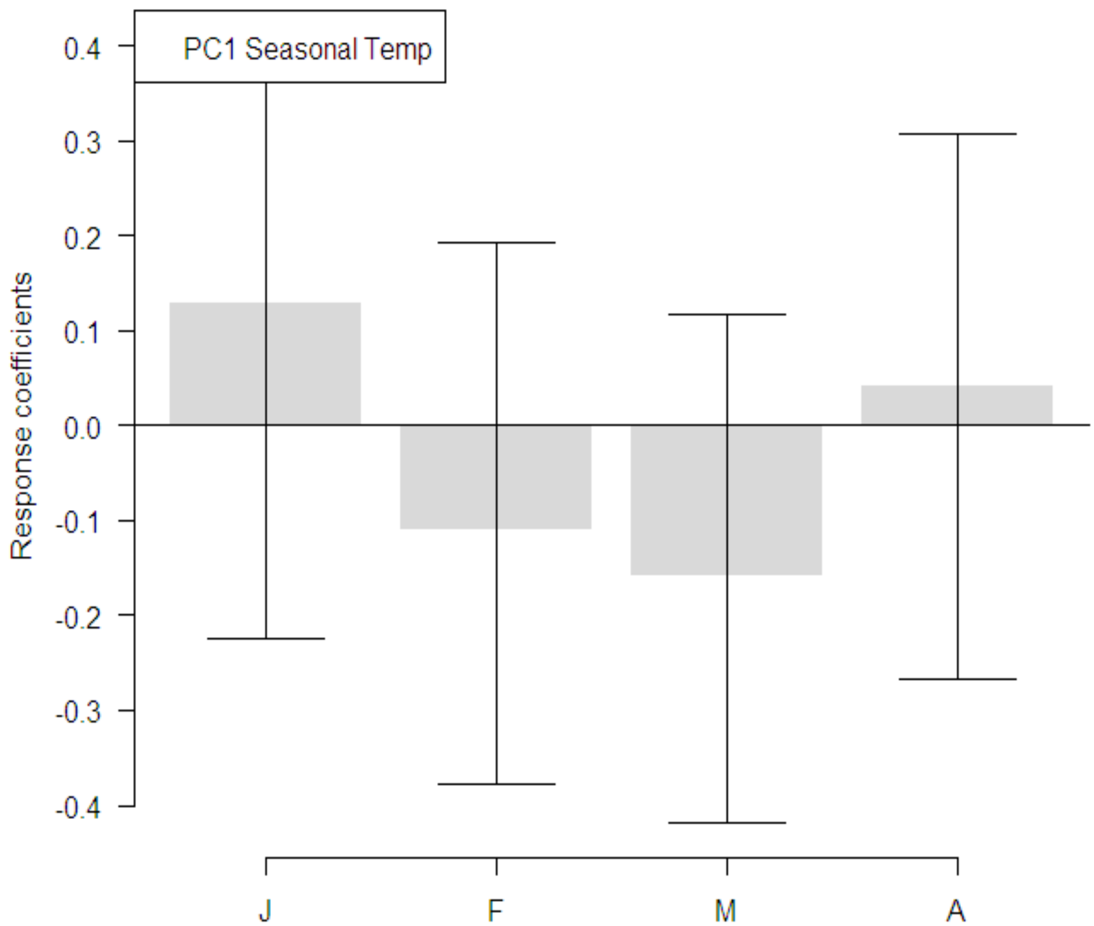

Figure 28 PC1 average temperature seasonally grouped response coefficient

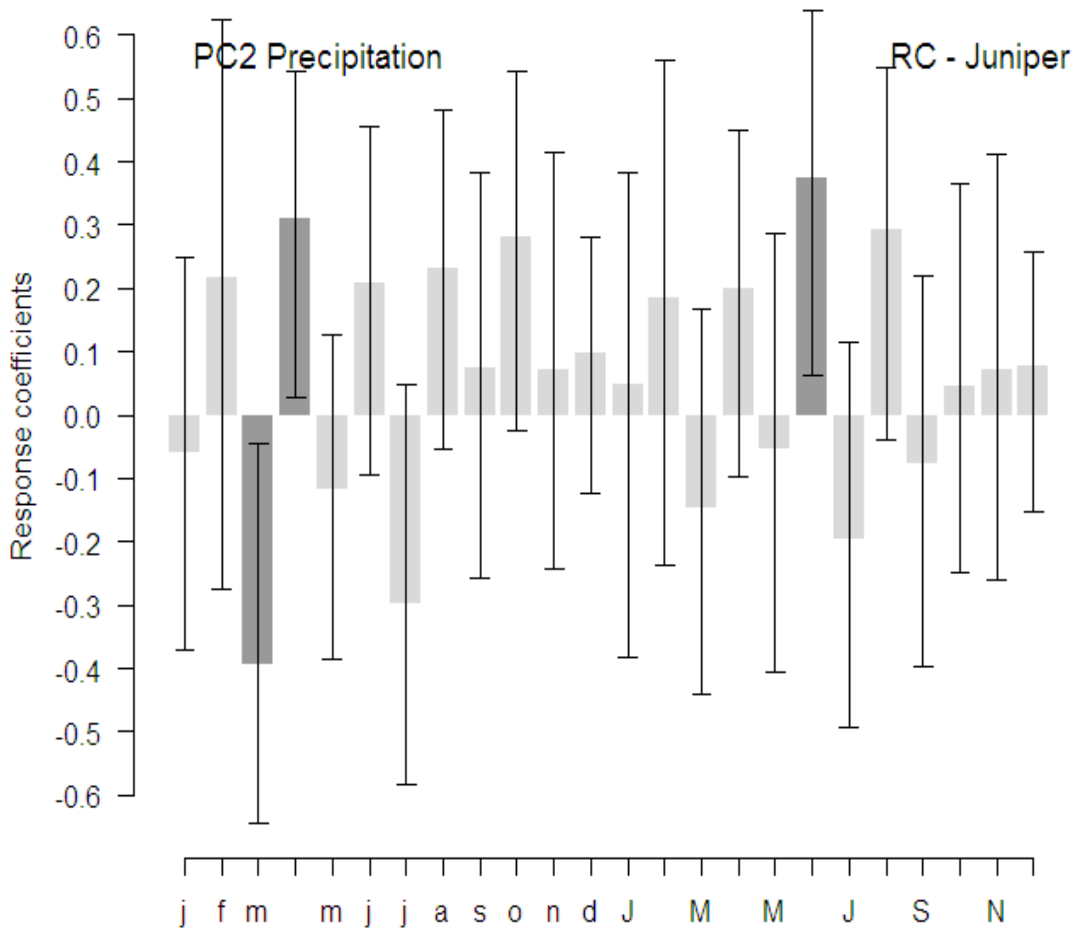

Figure 29 PC2 precipitation monthly response coefficient

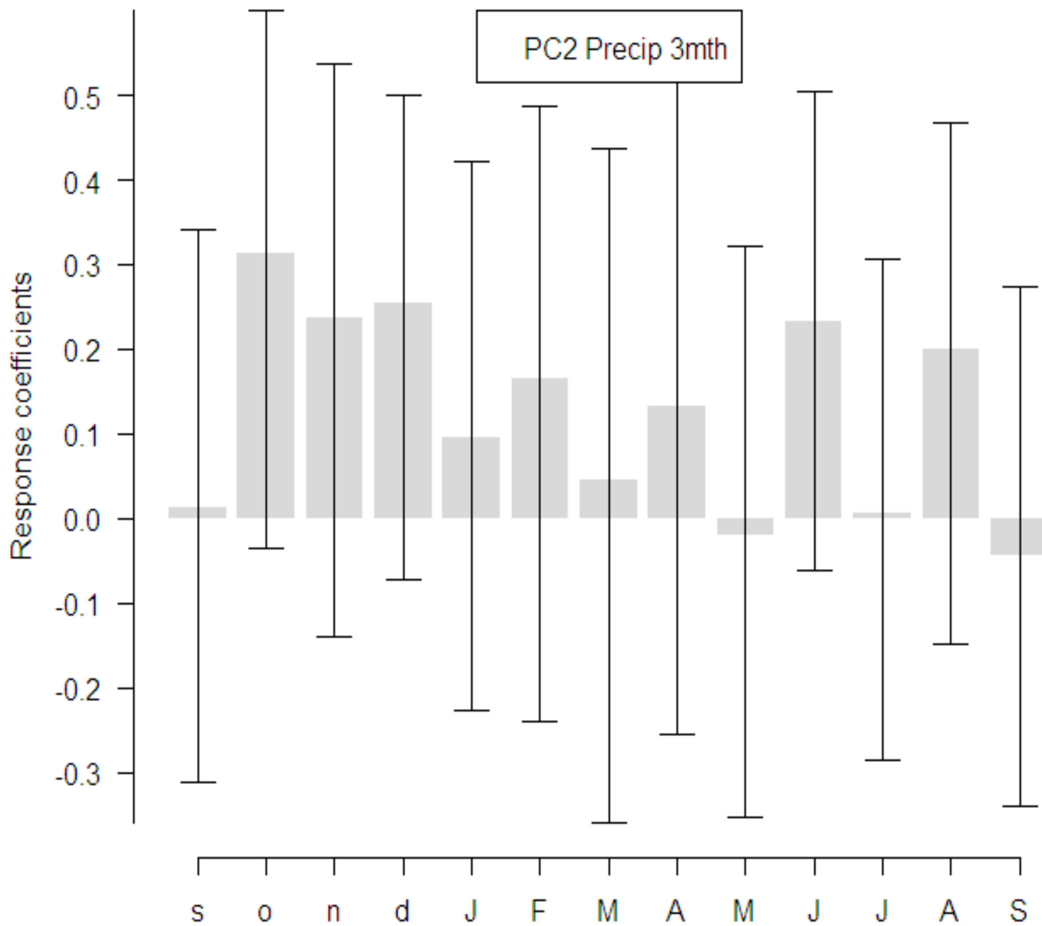

Figure 30 PC2 precipitation three month grouped response coefficient

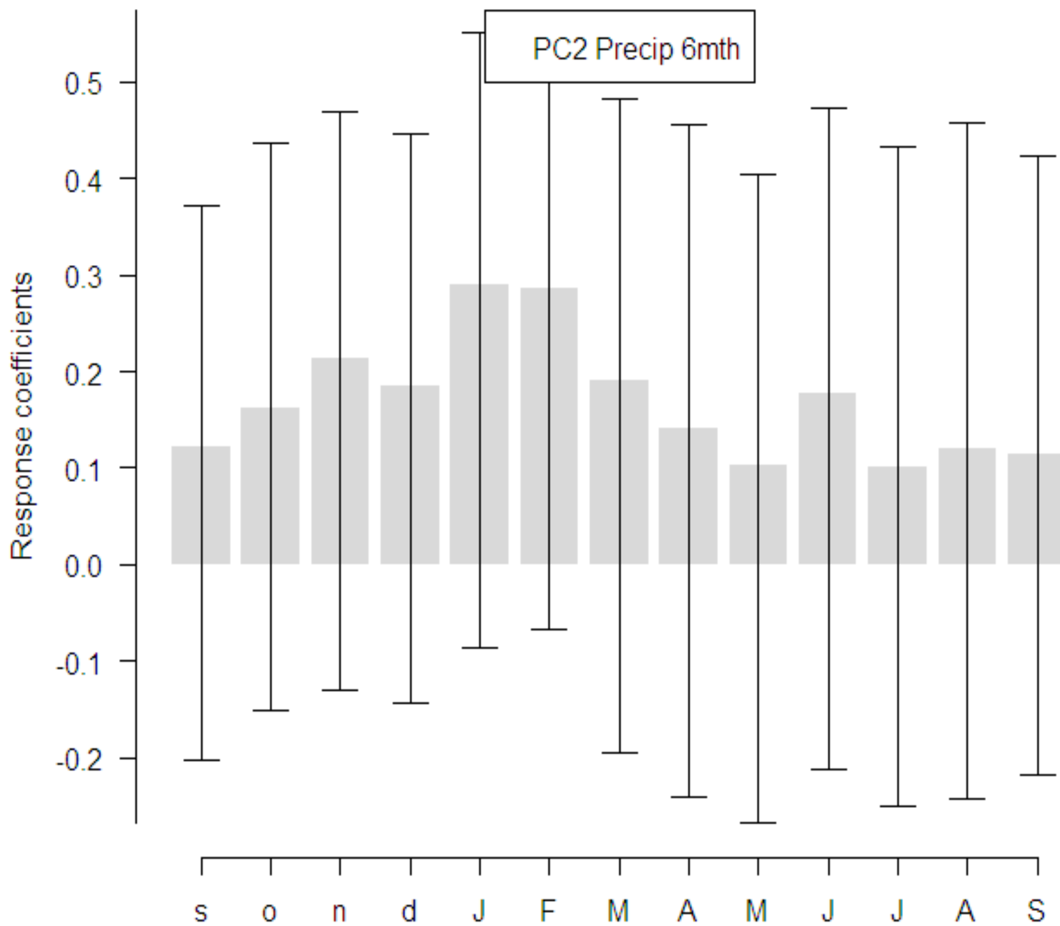

Figure 31 PC2 precipitation six month grouped response coefficient

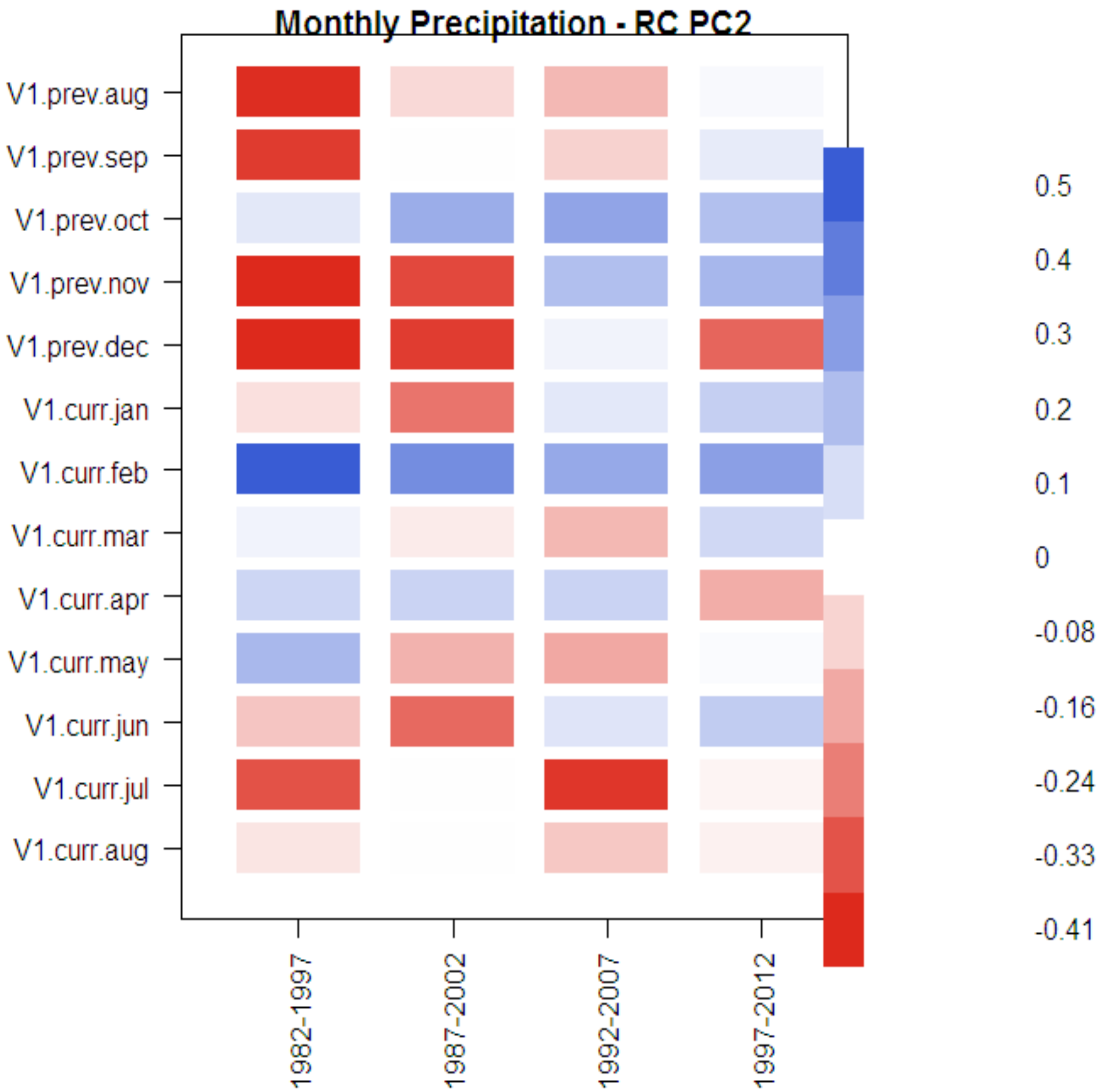

Figure 32 PC2 precipitation monthly response coefficient over time

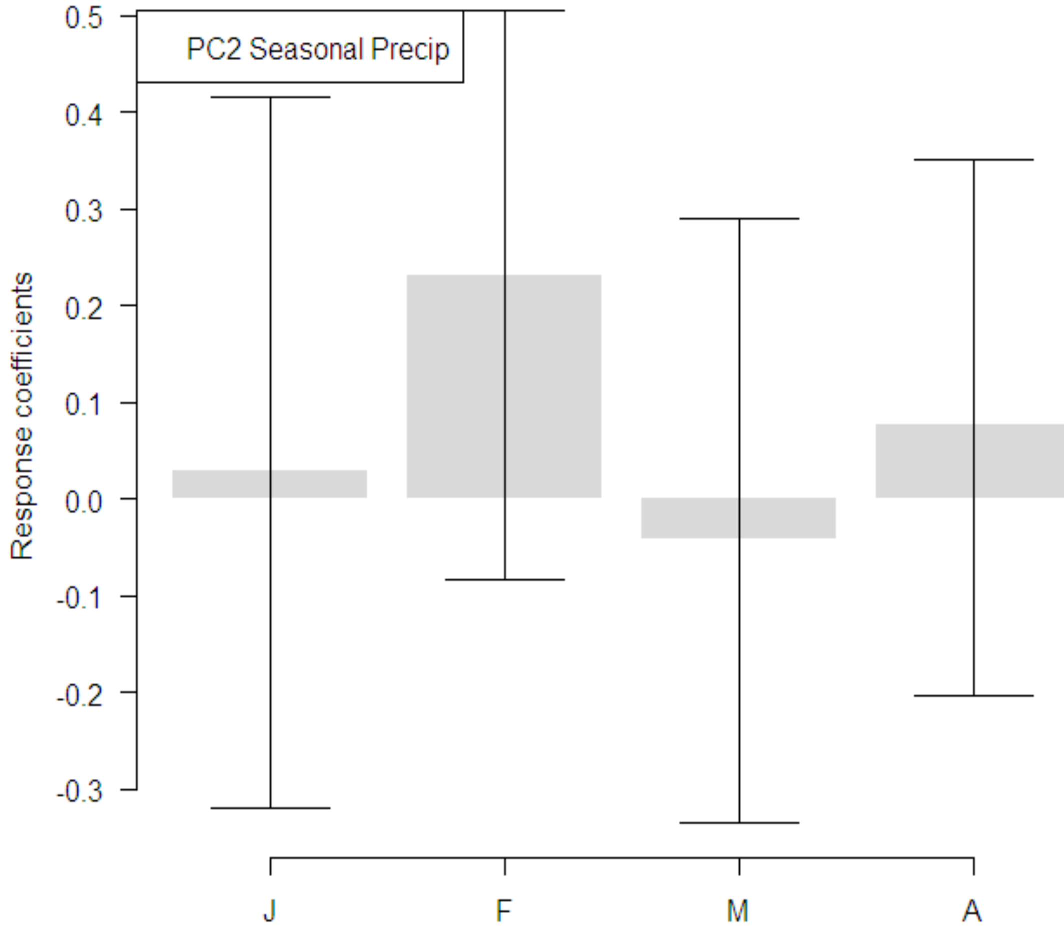

Figure 33 PC2 precipitation seasonally grouped response coefficient

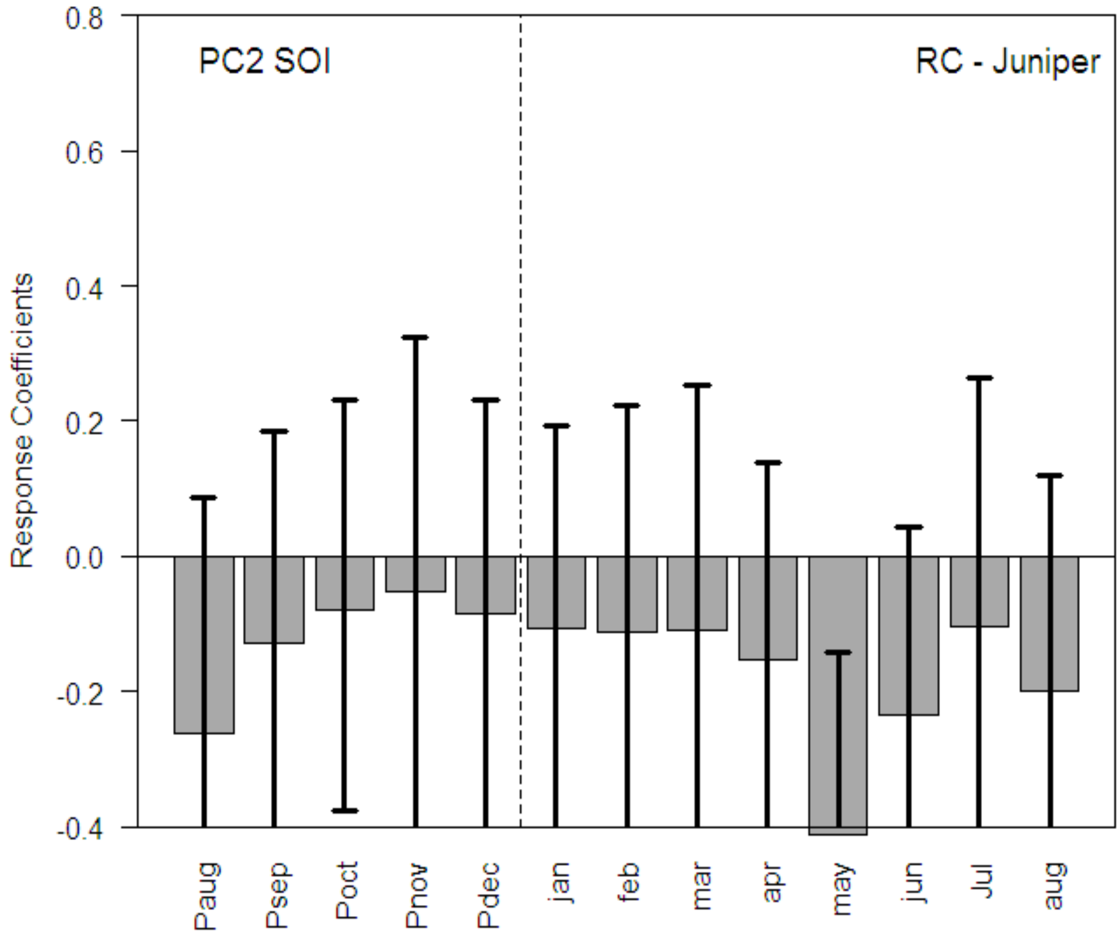

Figure 34 PC2 southern oscillation index monthly response coefficient

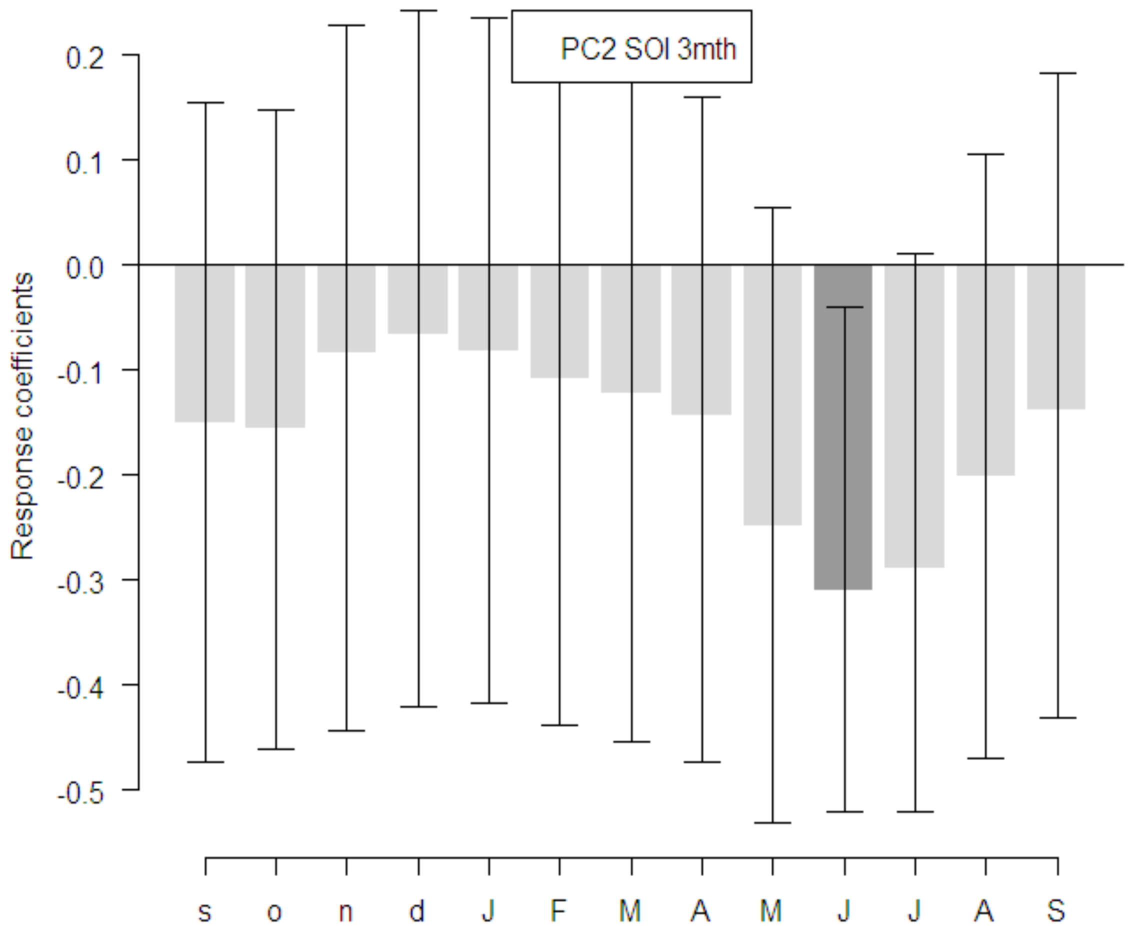

Figure 35 PC2 southern oscillation index three month grouped response coefficient

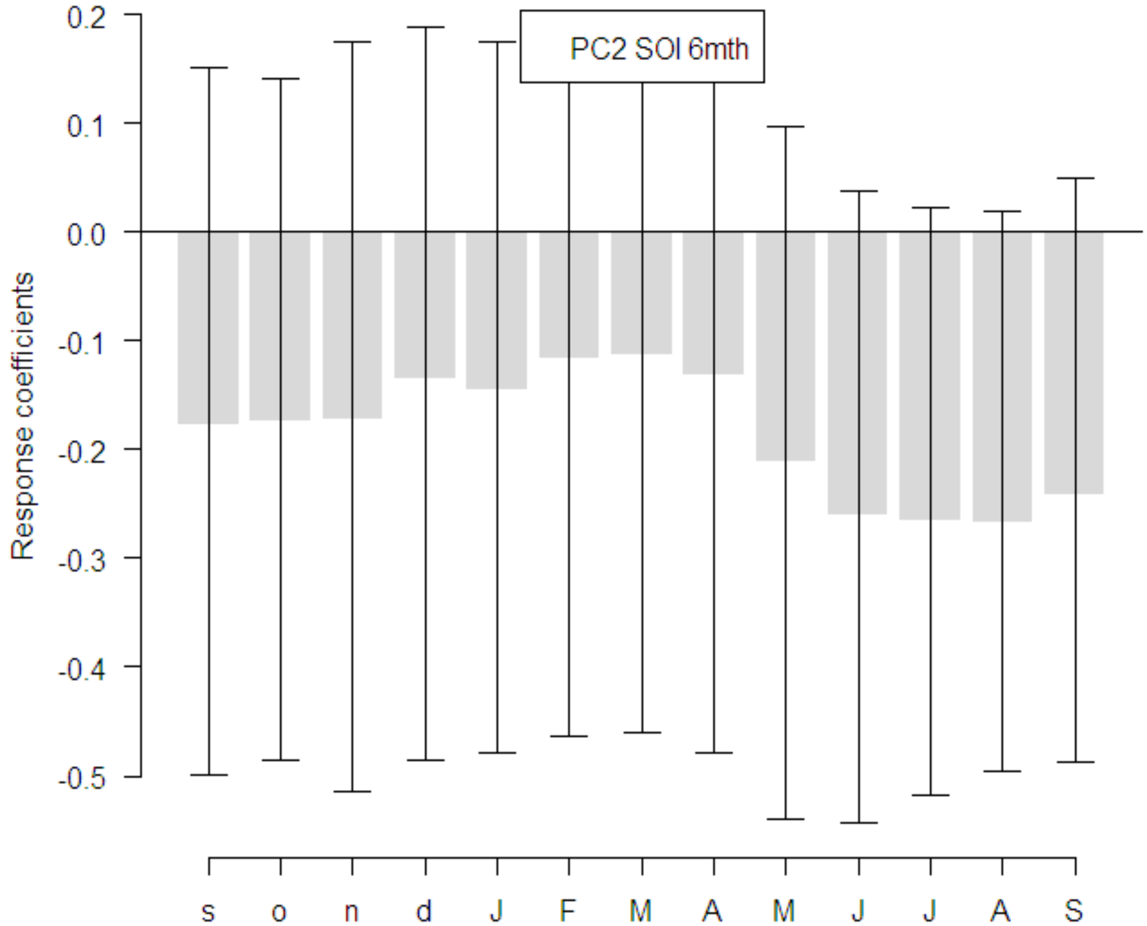

Figure 36 PC2 southern oscillation index six month grouped response coefficient

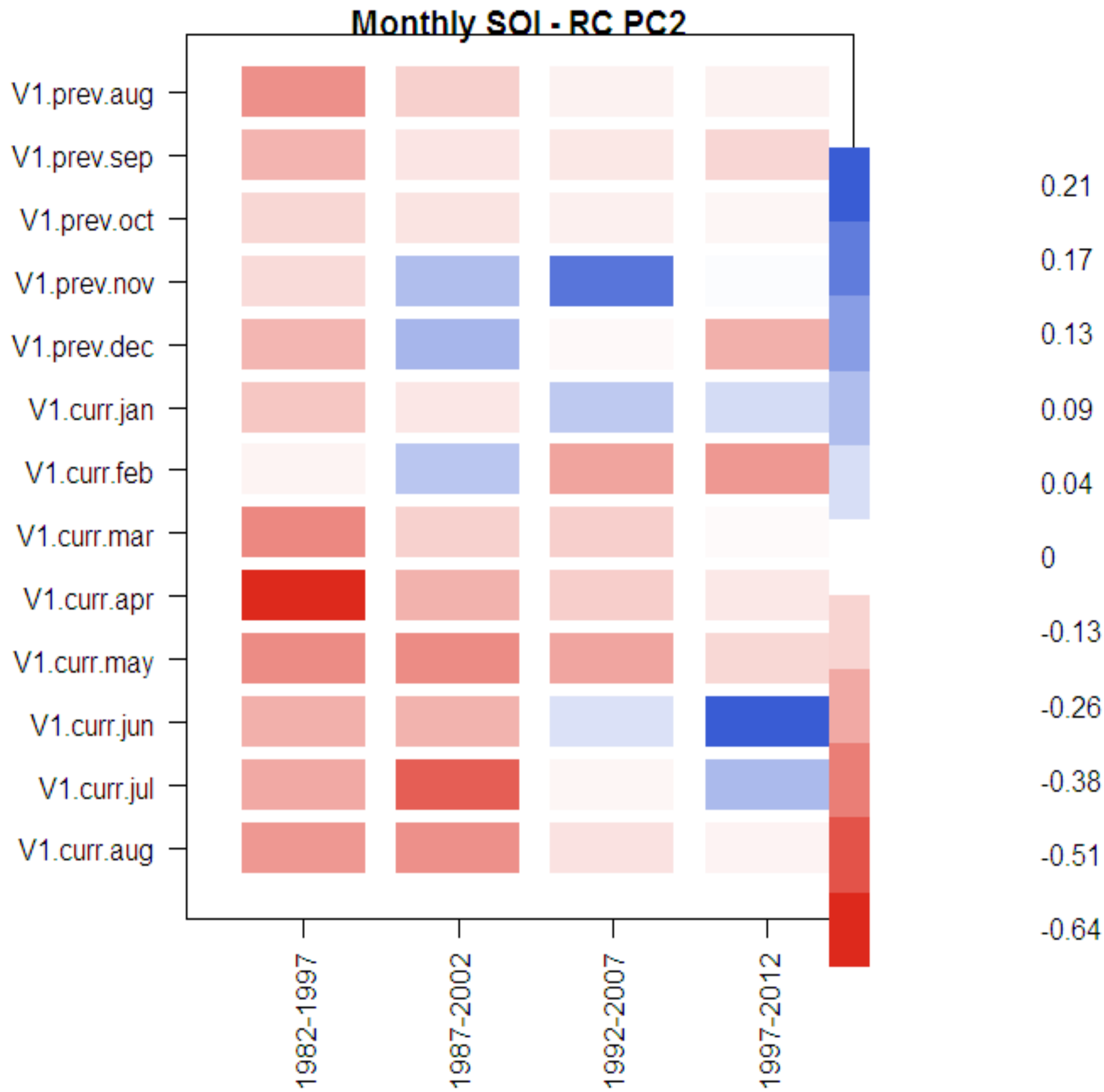

Figure 37 PC2 southern oscillation index monthly response coefficient over time

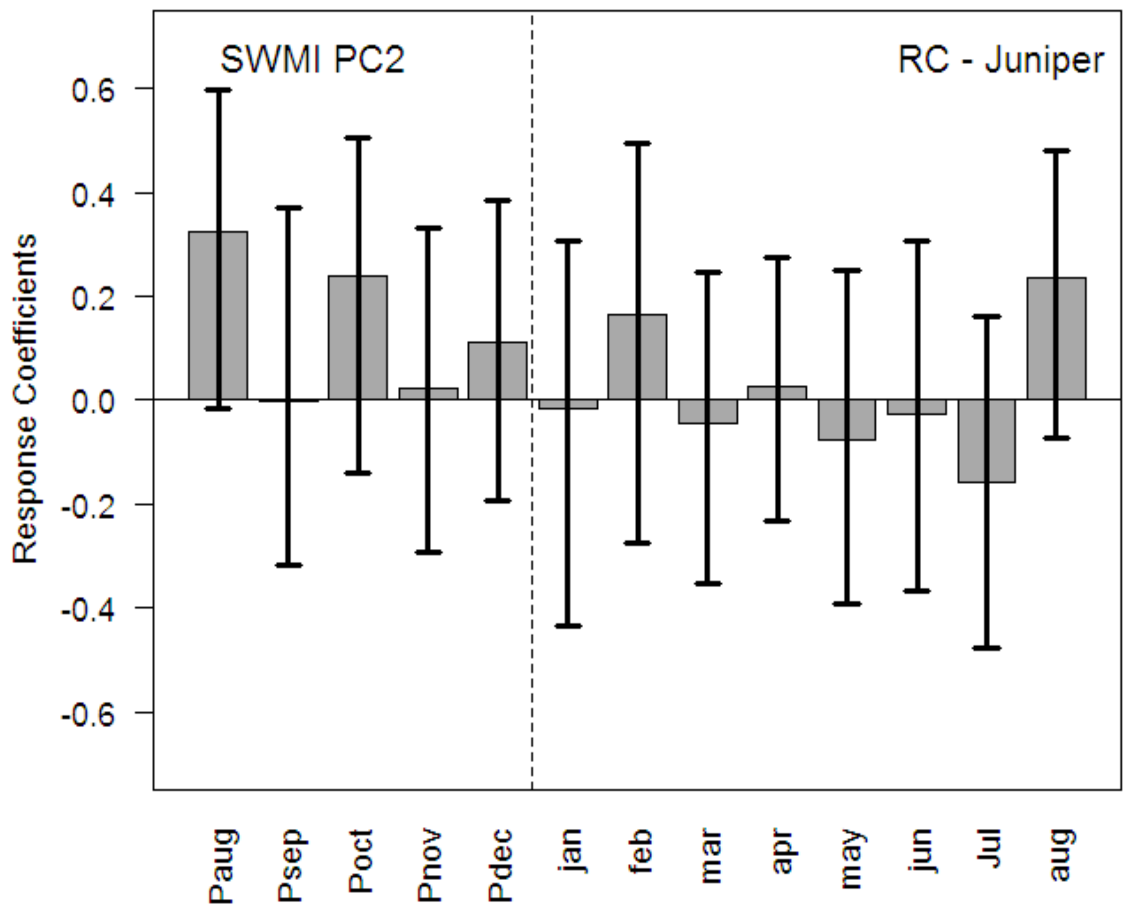

Figure 38 PC2 southwest monsoon index monthly response coefficient

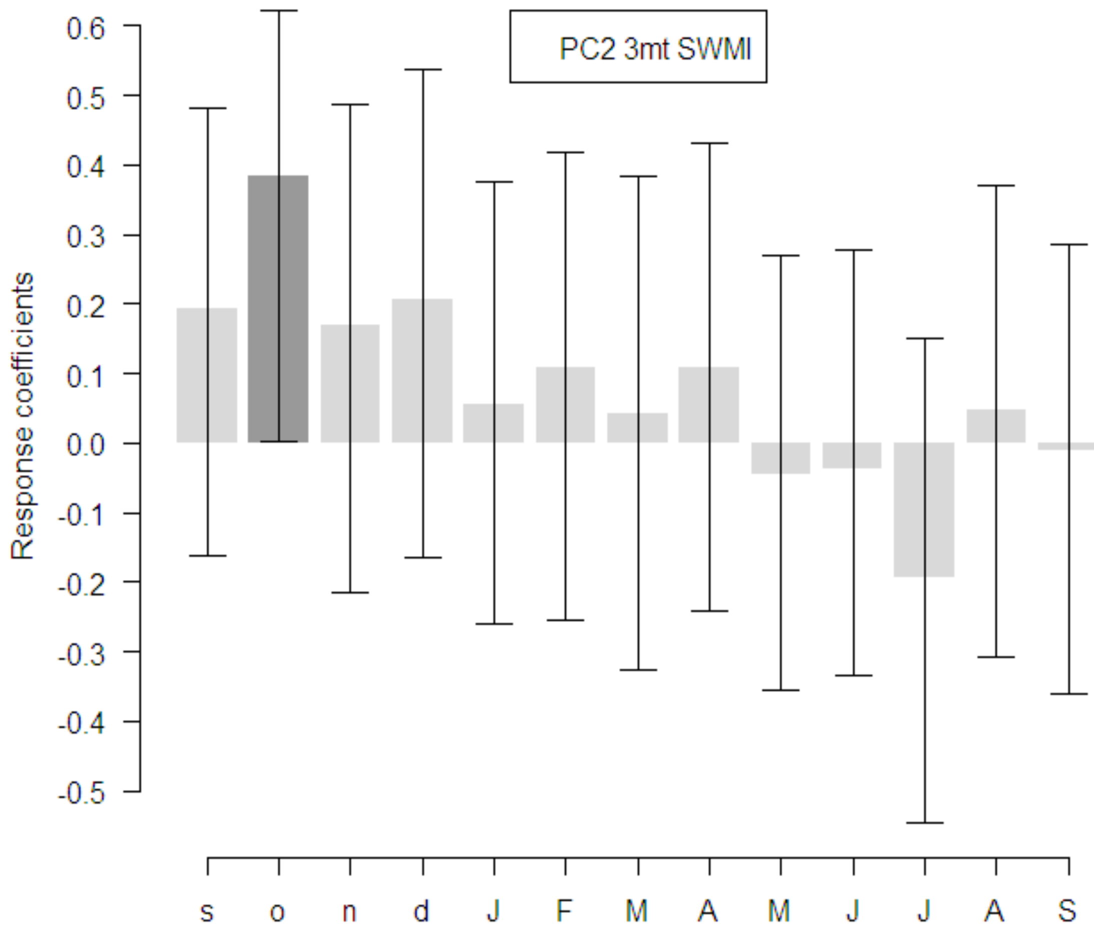

Figure 39 PC2 southwest monsoon index three month grouped response coefficient

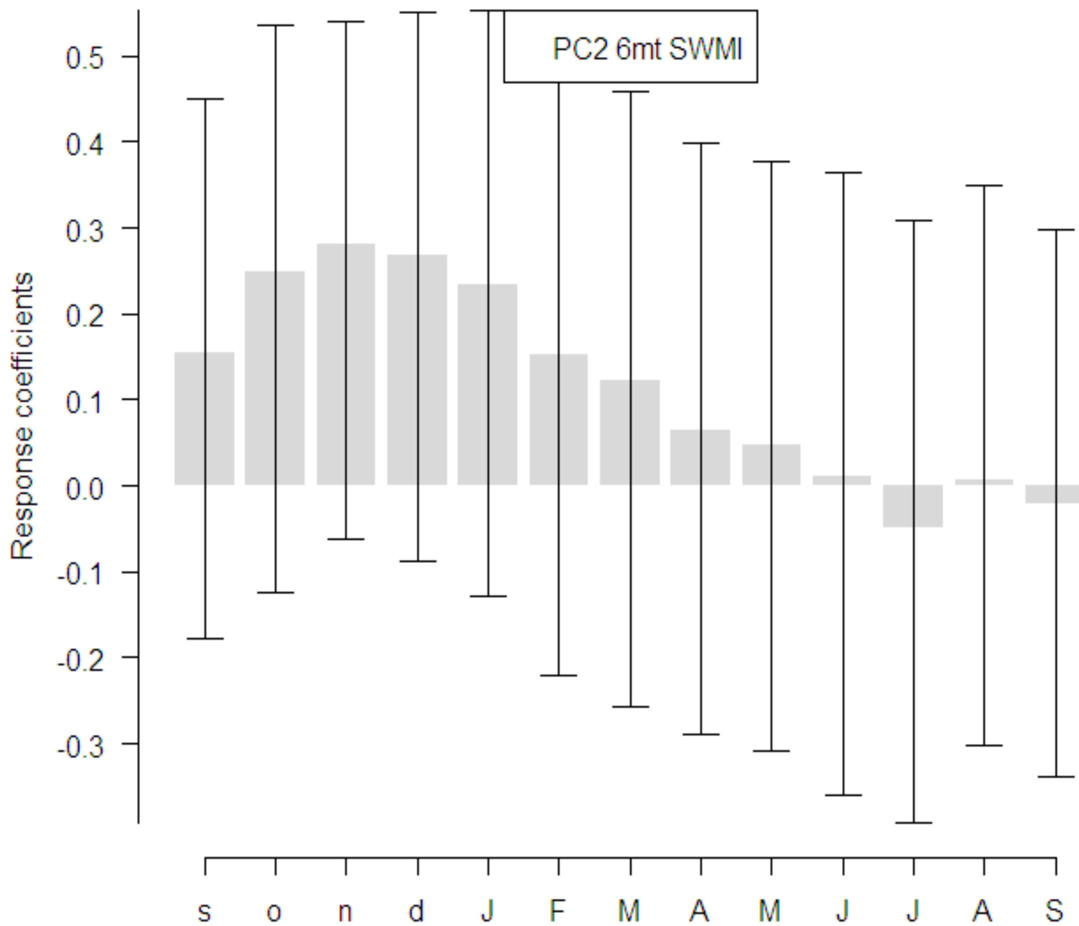

Figure 40 PC2 southwest monsoon index six month grouped response coefficient

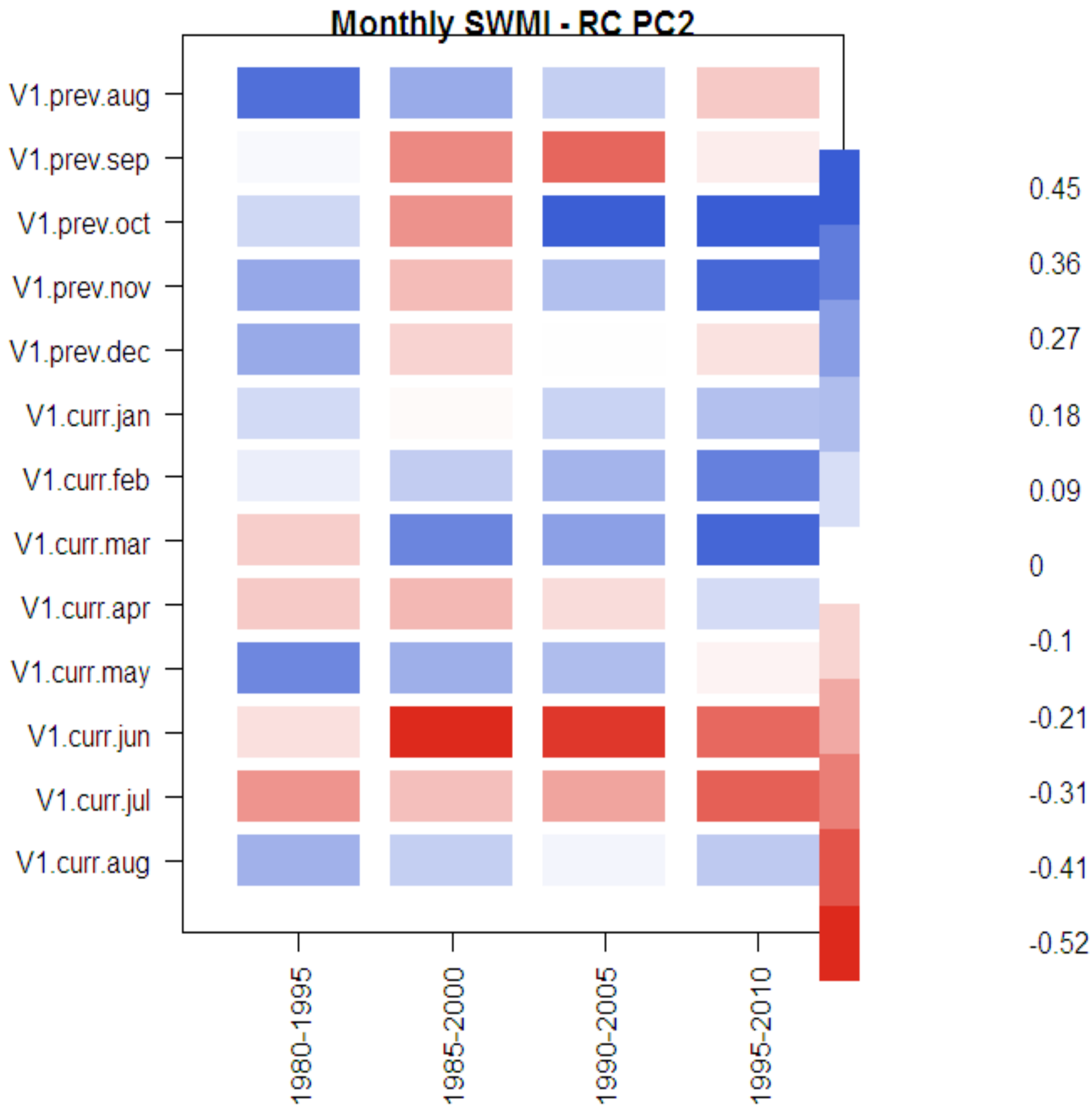

Figure 41 PC2 southwest monsoon index monthly response coefficient over time

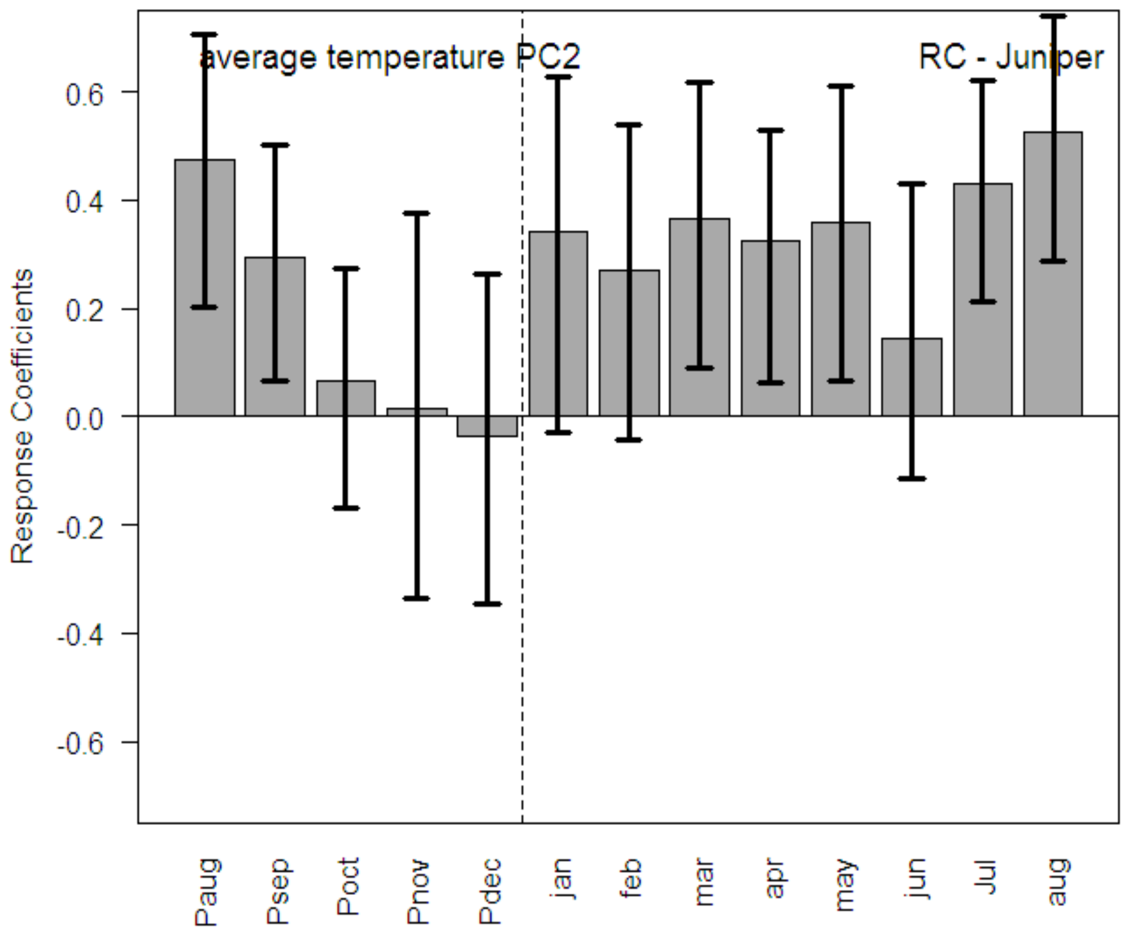

Figure 42 PC2 average temperature monthly response coefficient

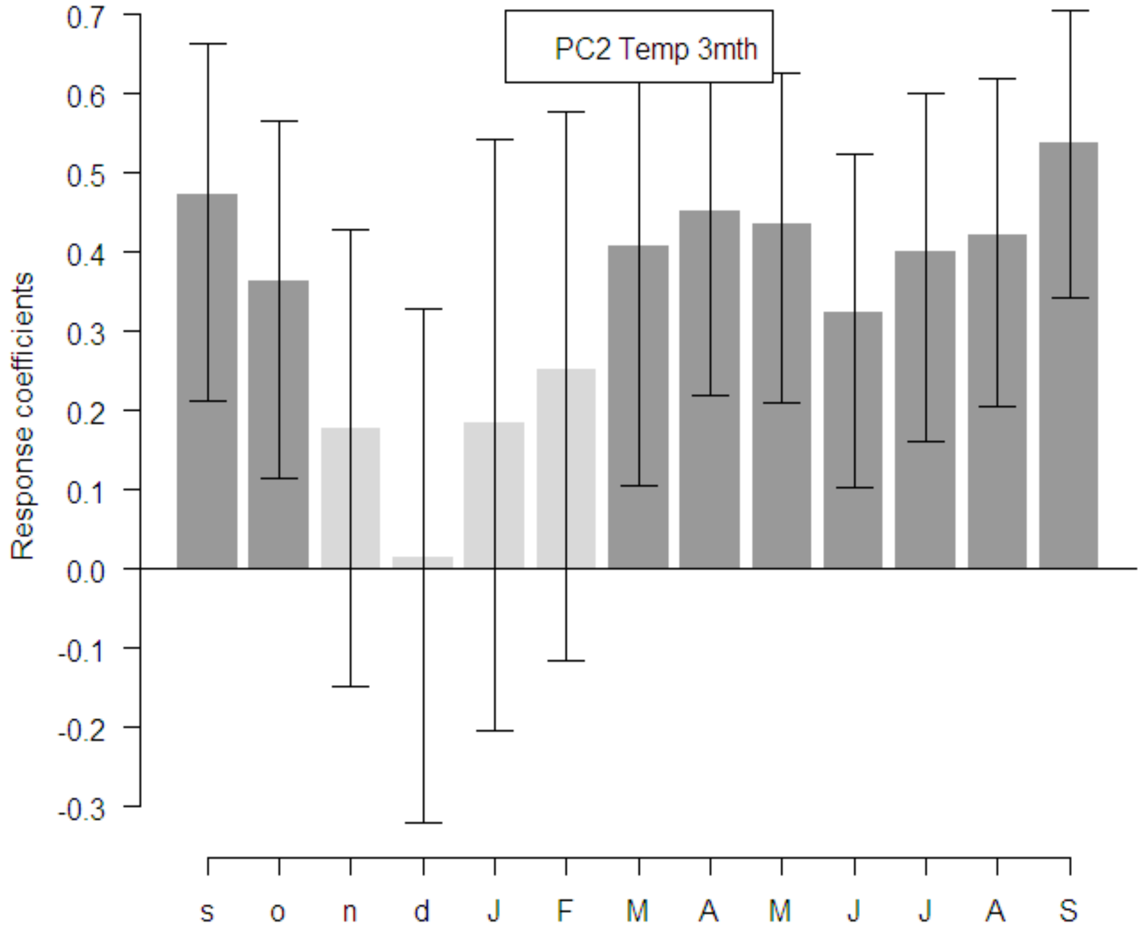

Figure 43 PC2 average temperature three month grouped response coefficient

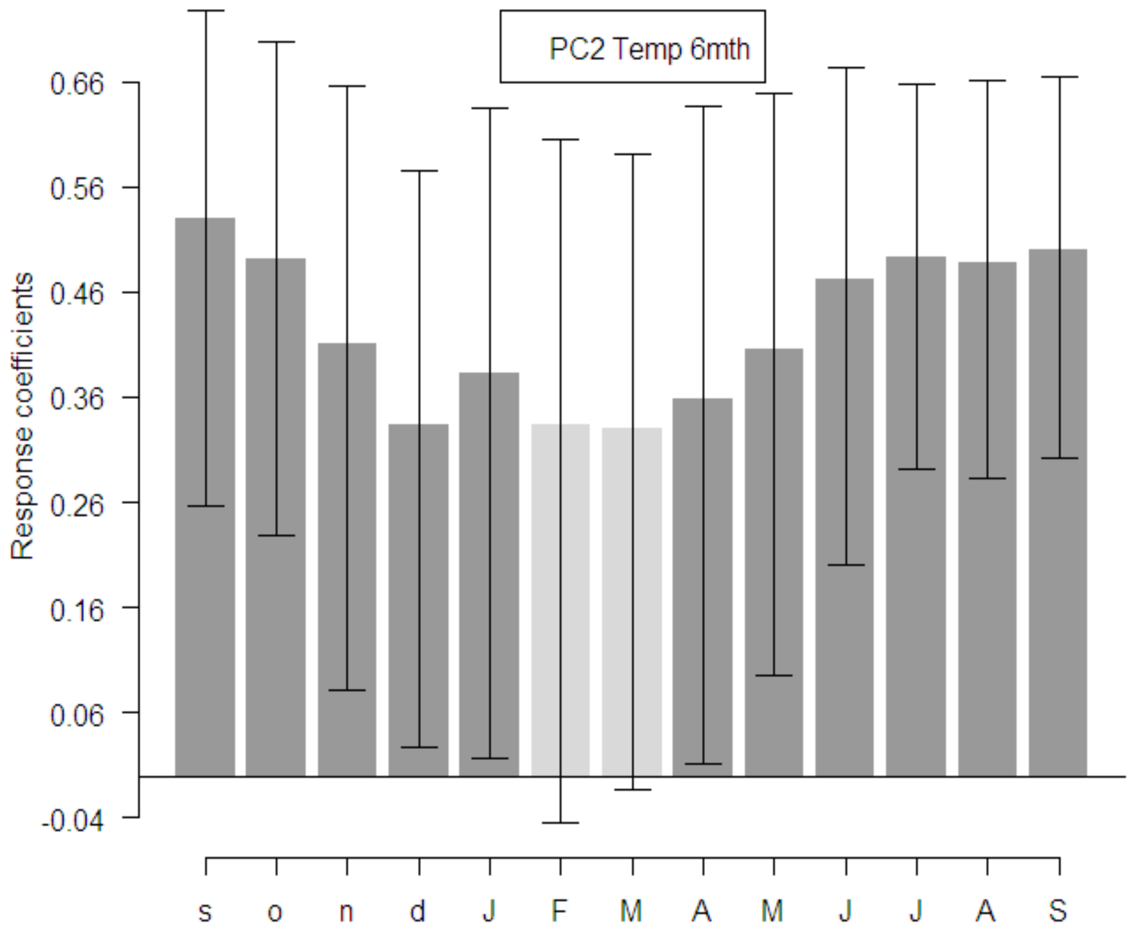

Figure 44 PC2 average temperature six month grouped response coefficient

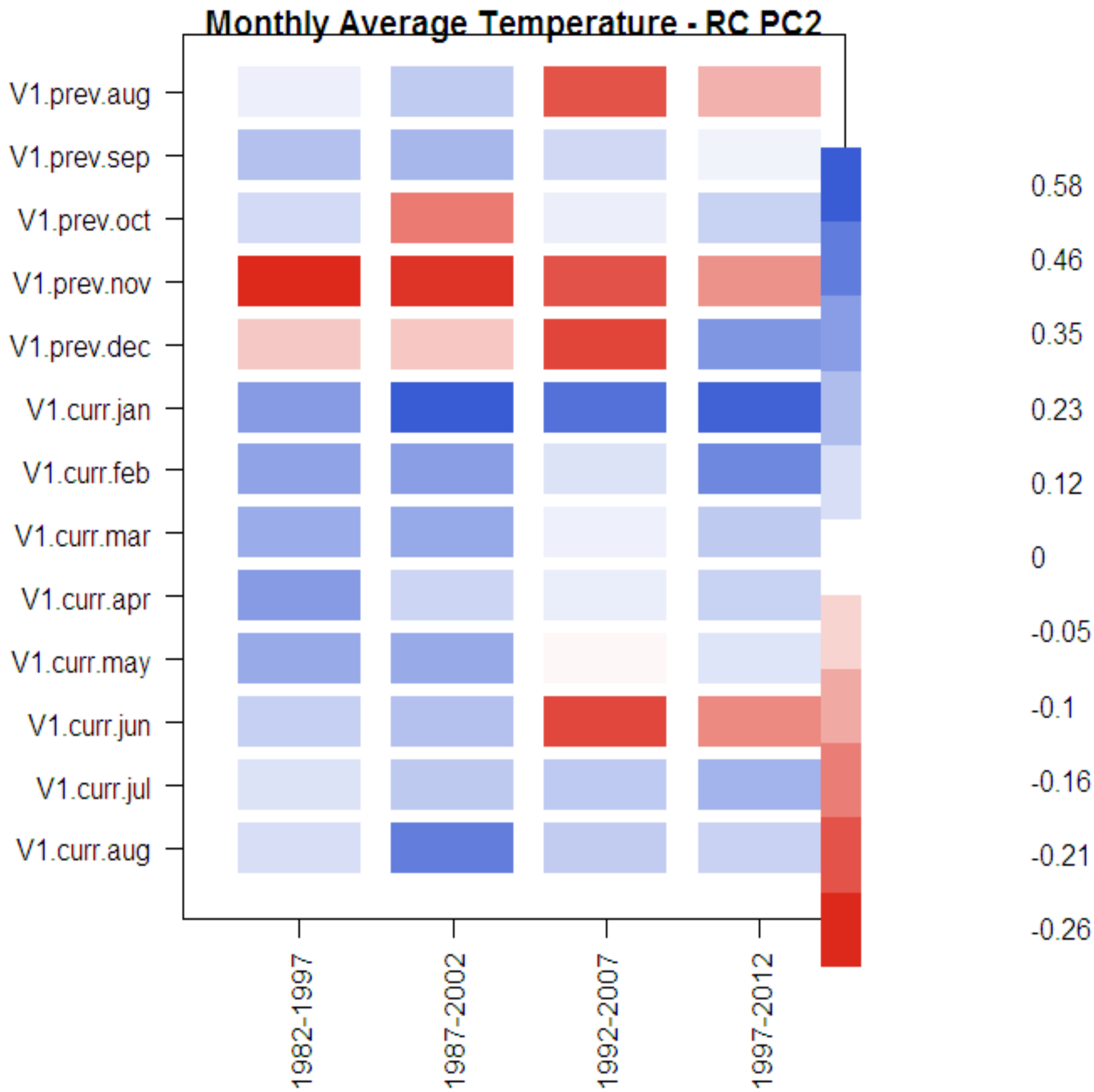

Figure 45 PC2 average temperature monthly response coefficient

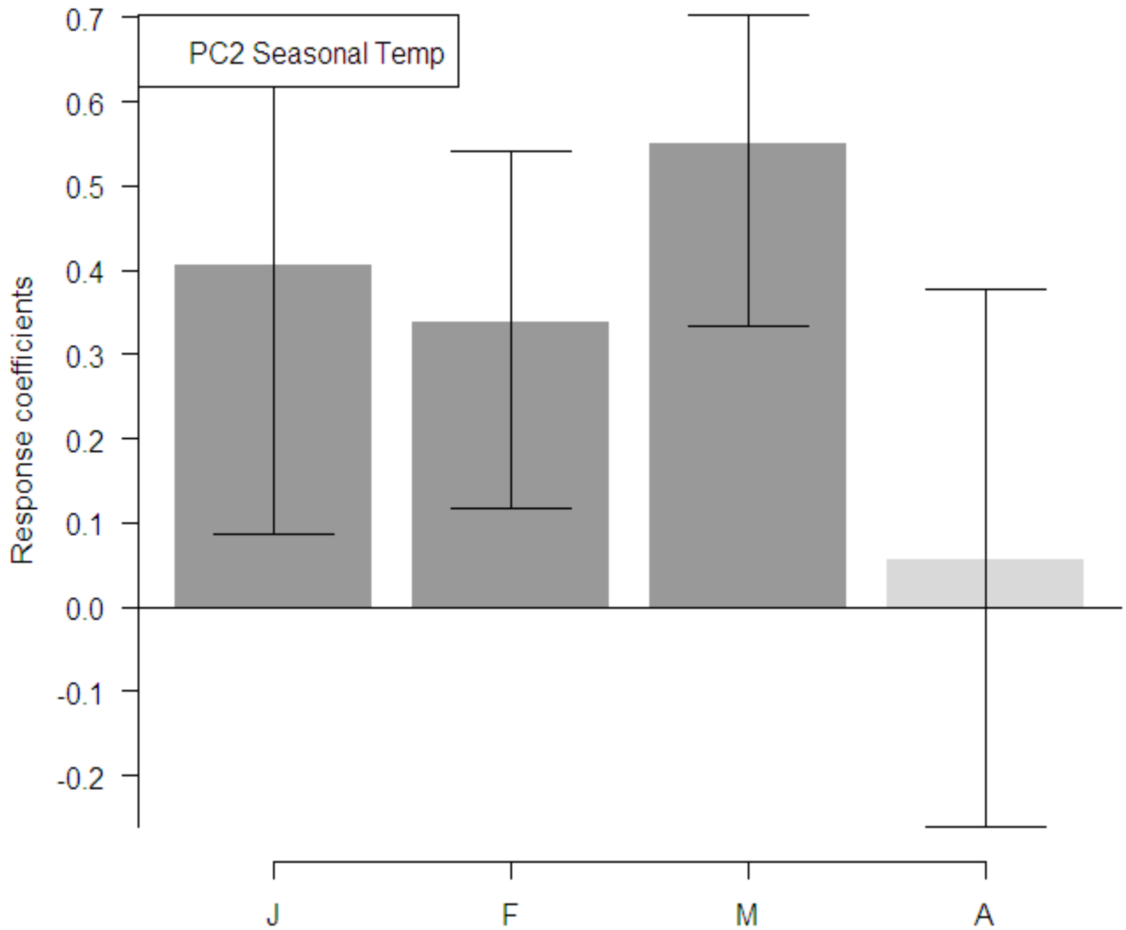

Figure 46 PC2 average temperature seasonally grouped response coefficient

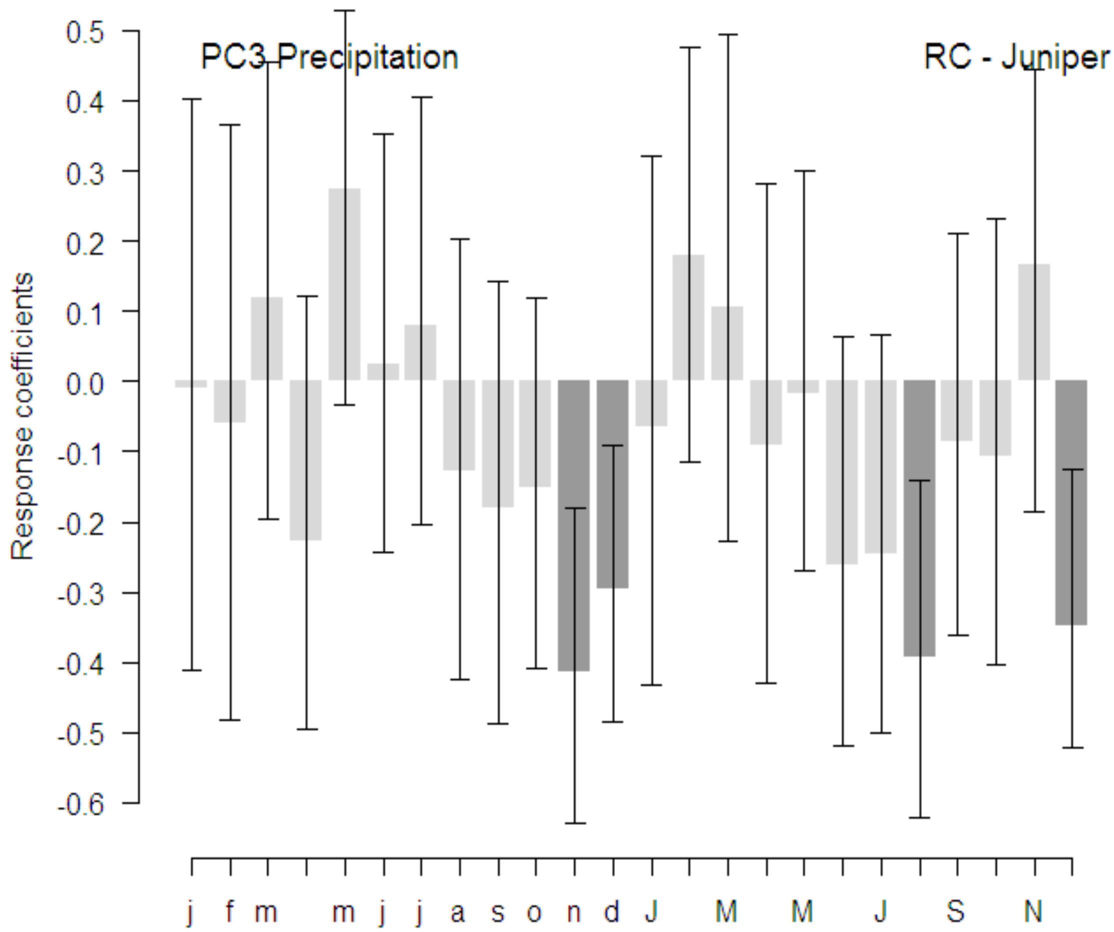

Figure 47 PC3 precipitation monthly response coefficient

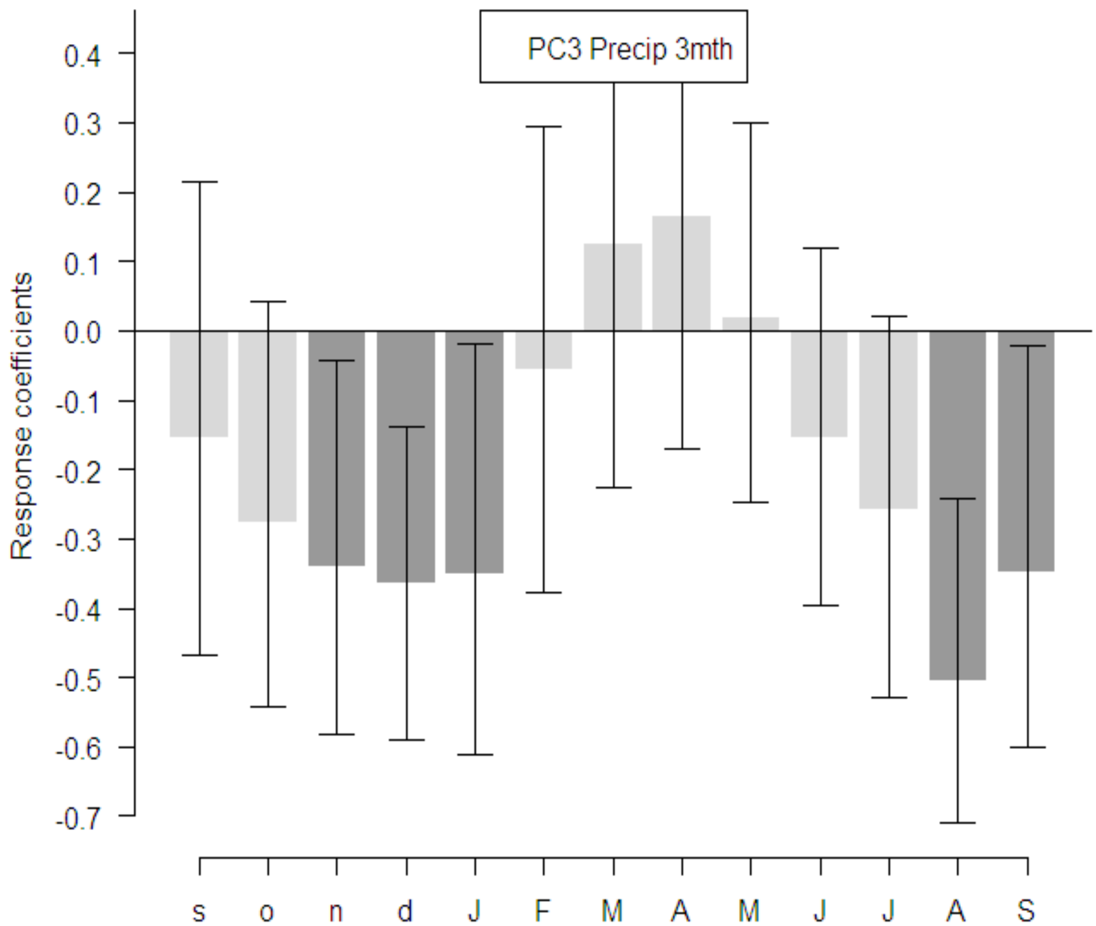

Figure 48 PC3 precipitation three month grouped response coefficient

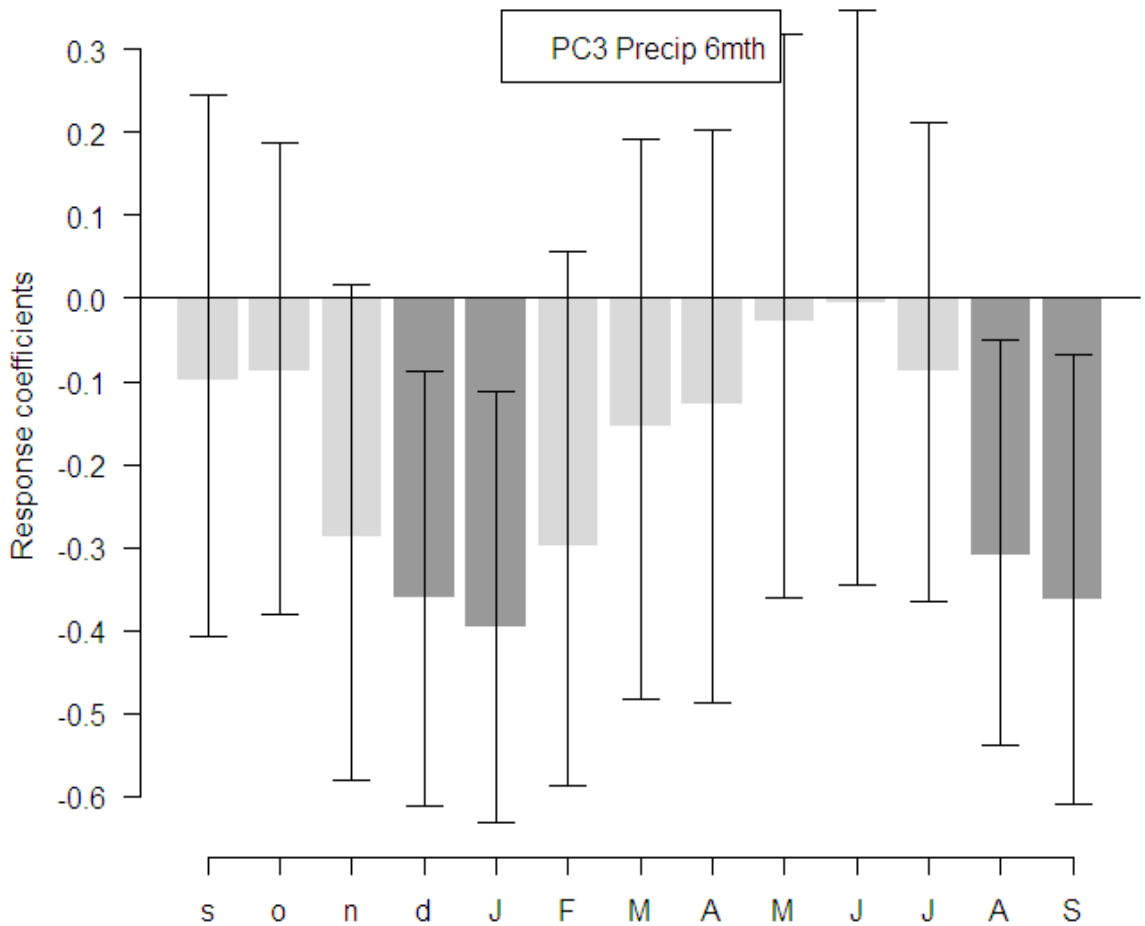

Figure 49 PC3 precipitation six month grouped response coefficient

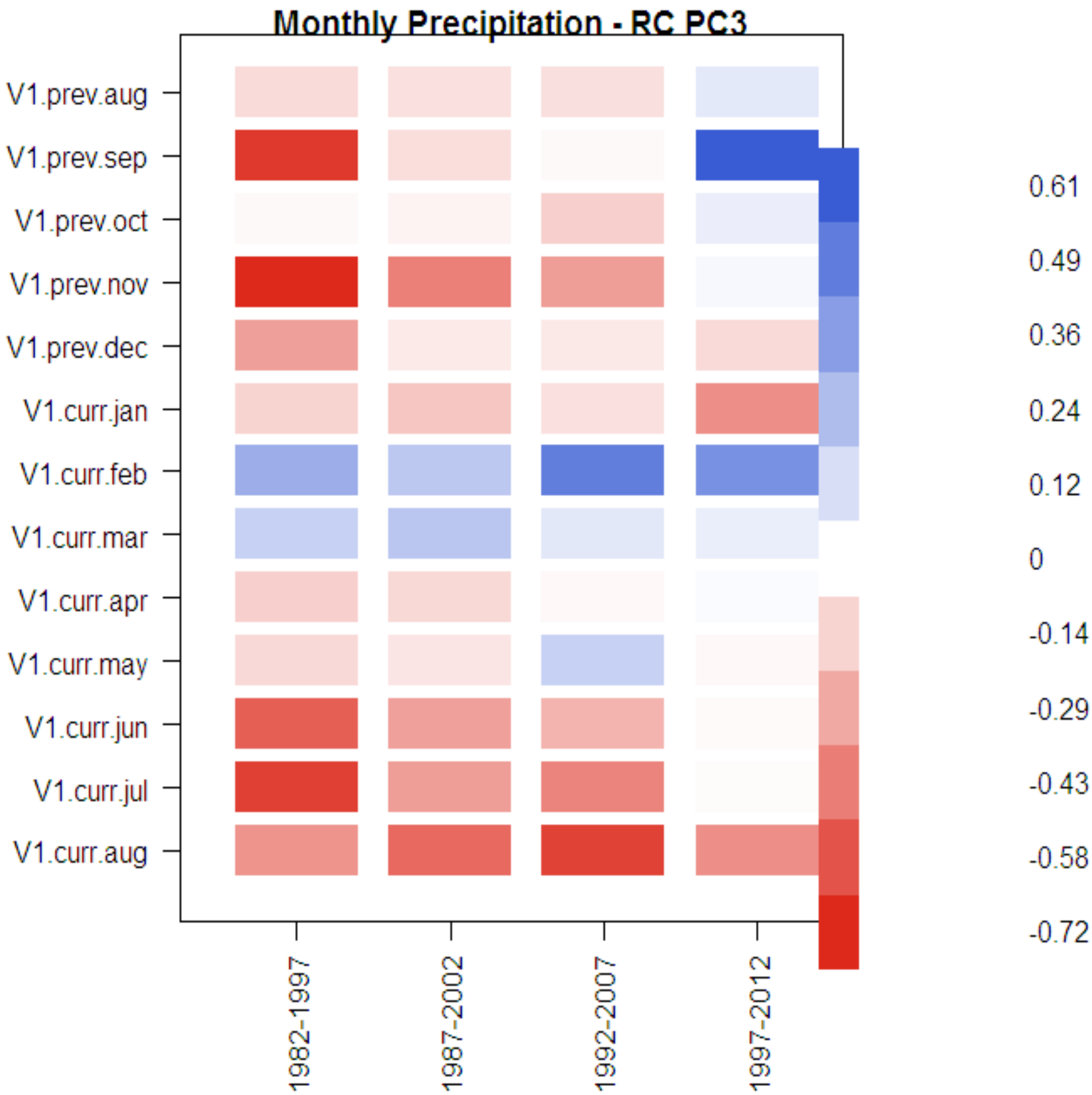

Figure 50 PC3 precipitation monthly response coefficient over time

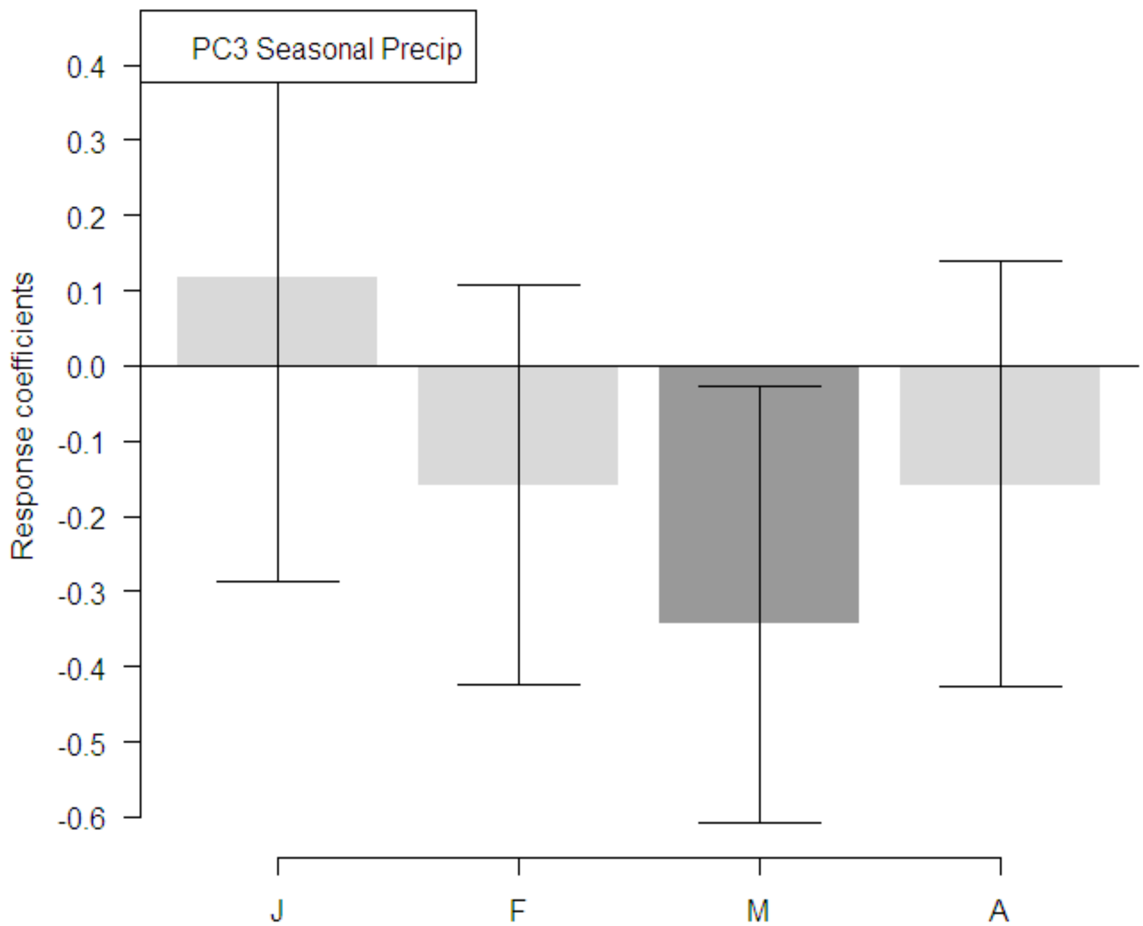

Figure 51 PC3 precipitation seasonally grouped response coefficient

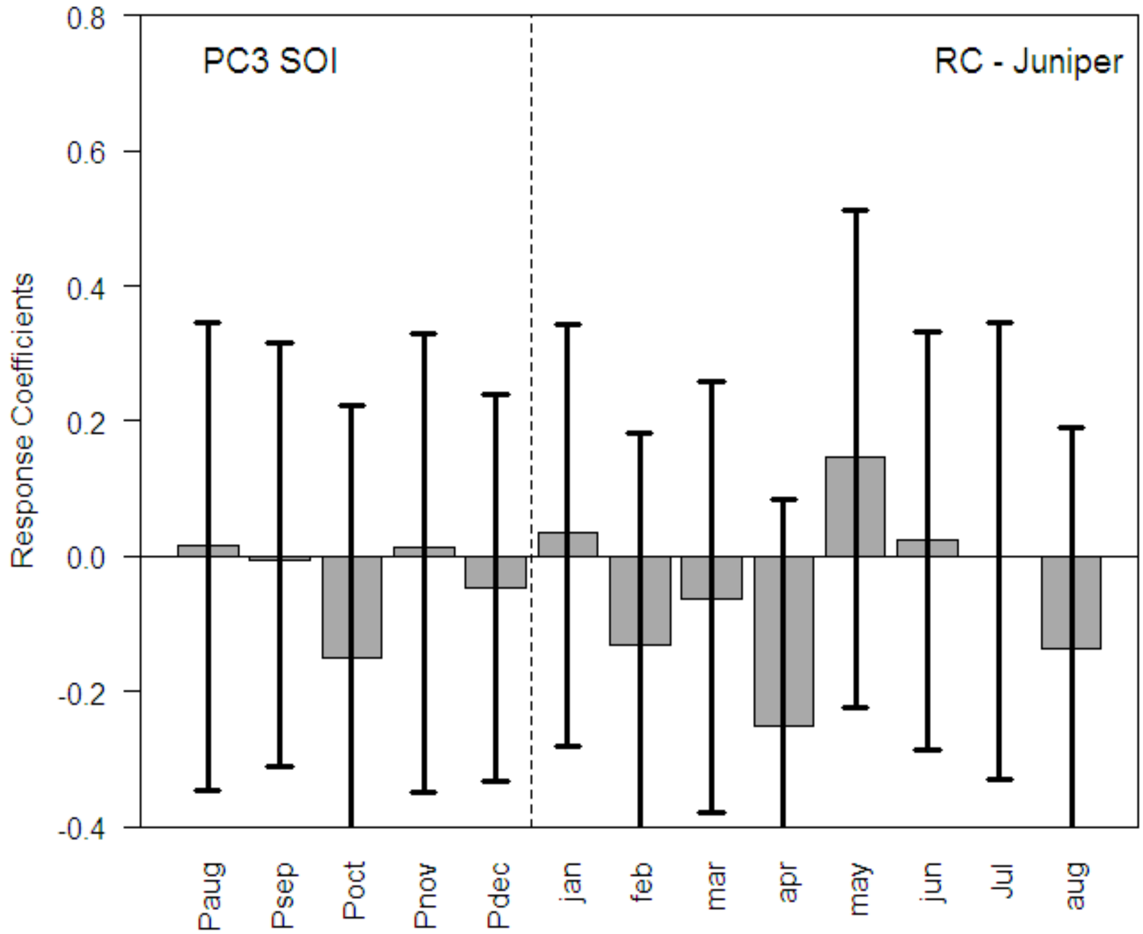

Figure 52 PC3 southern oscillation index monthly response coefficient

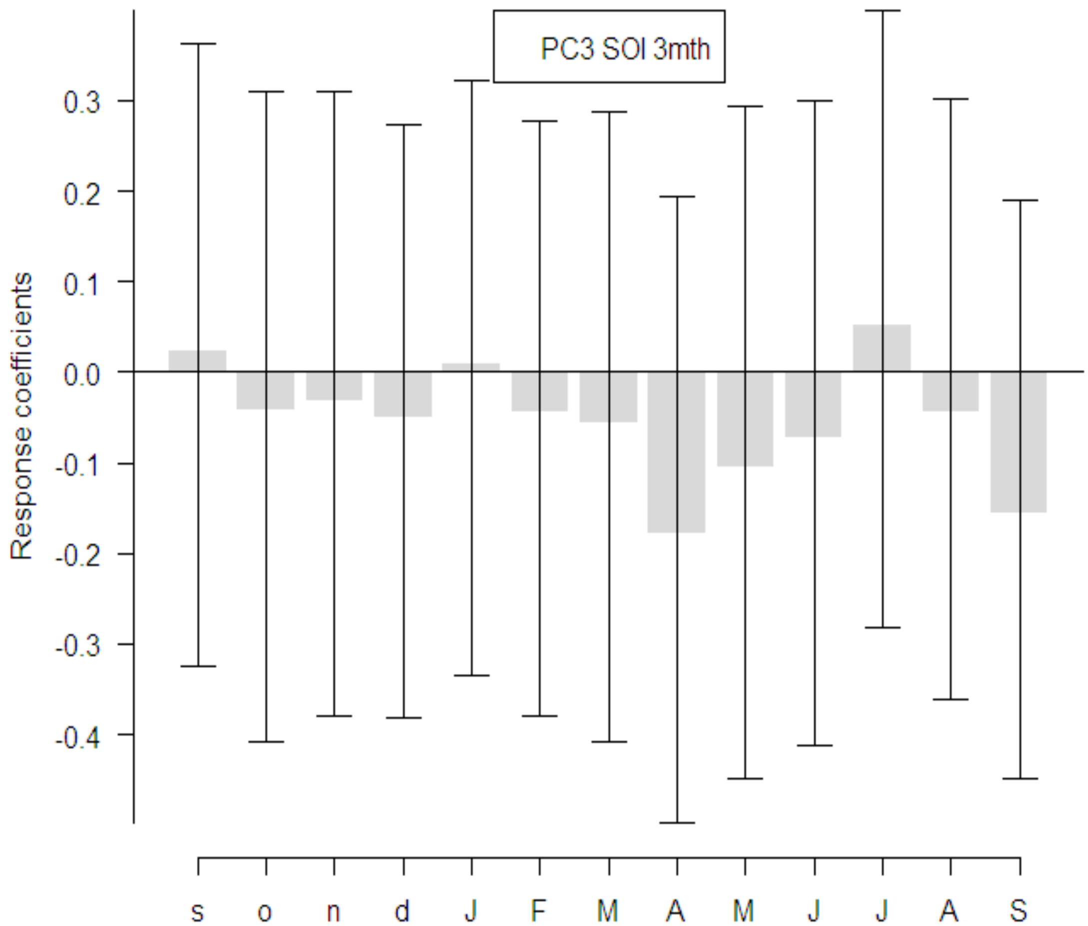

Figure 53 PC3 southern oscillation index three month grouped response coefficient

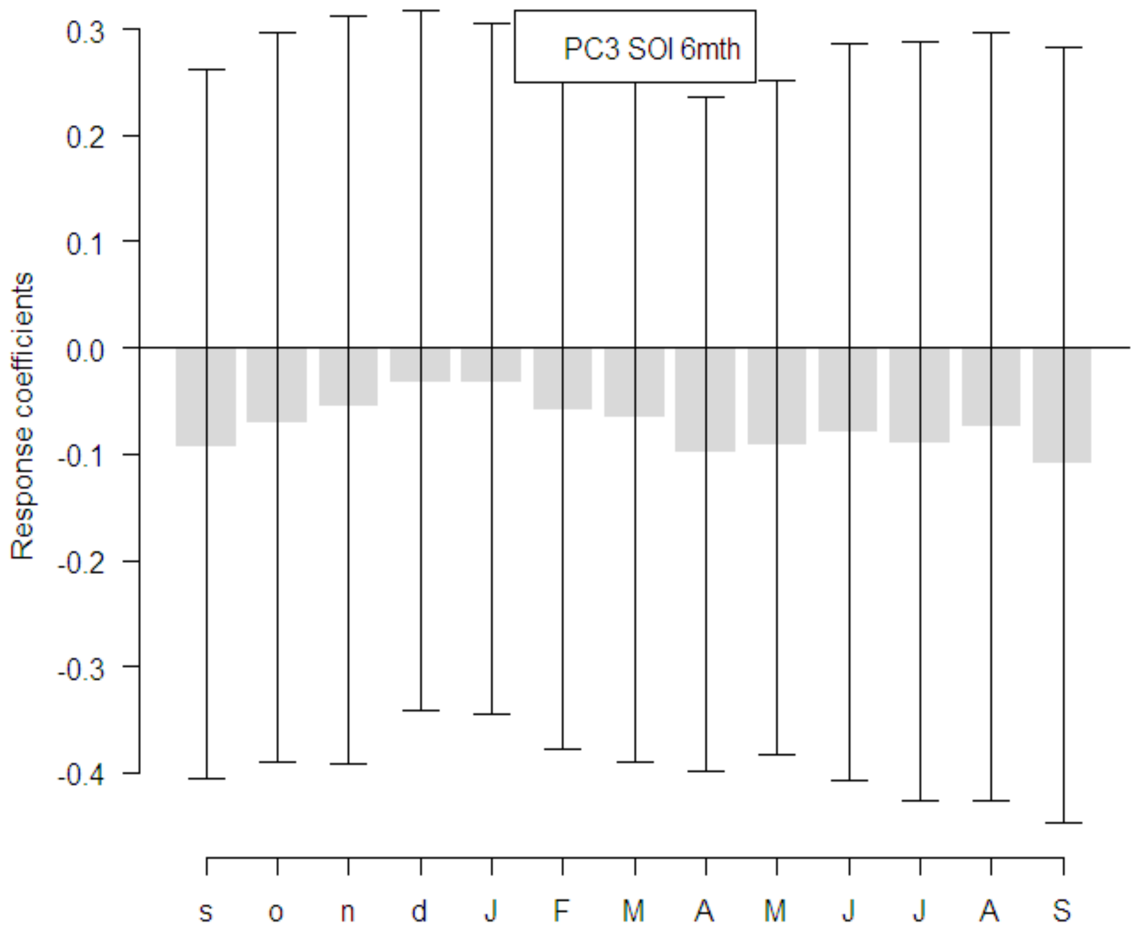

Figure 54 PC3 southern oscillation index six month grouped response coefficient

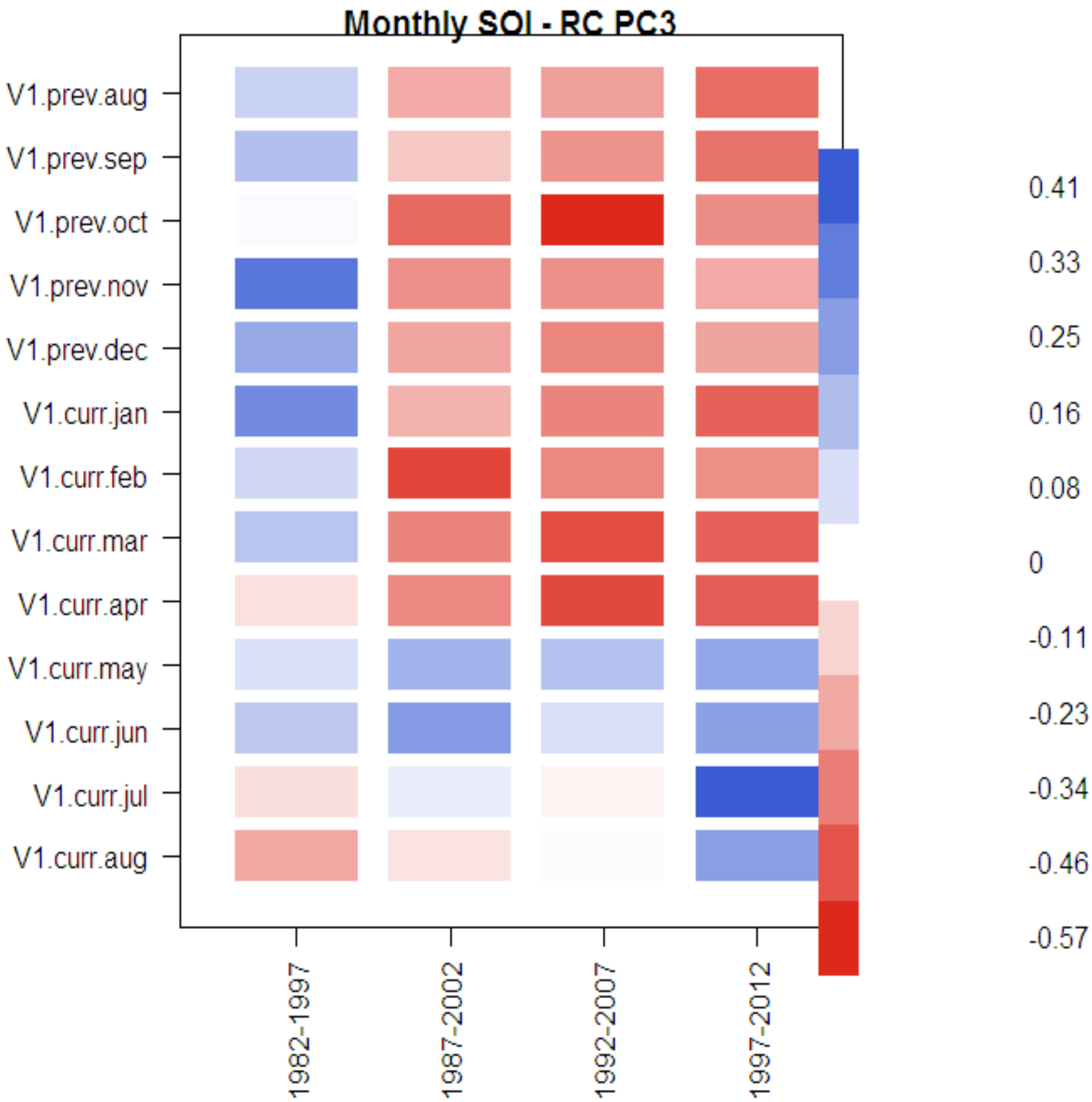

Figure 55 PC3 southern oscillation index monthly response coefficient over time

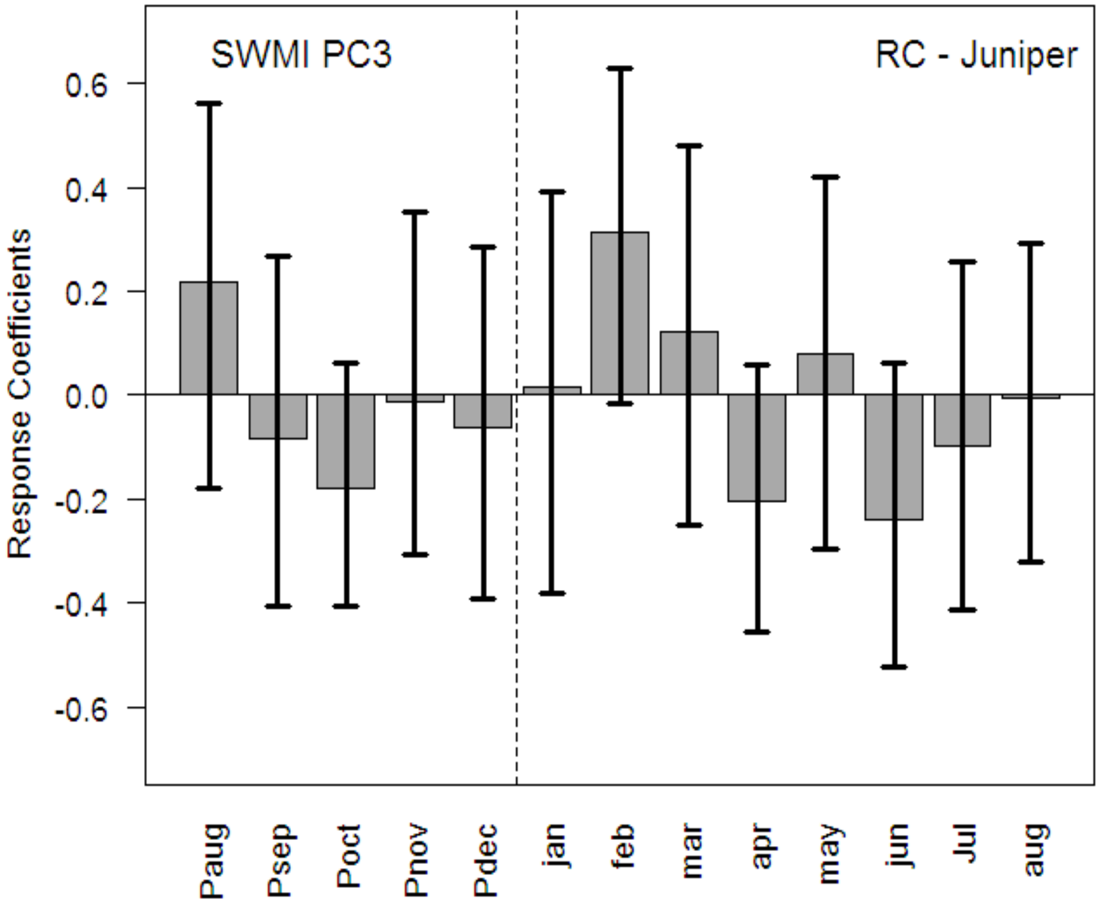

Figure 56 PC3 southwest monsoon index monthly response coefficient

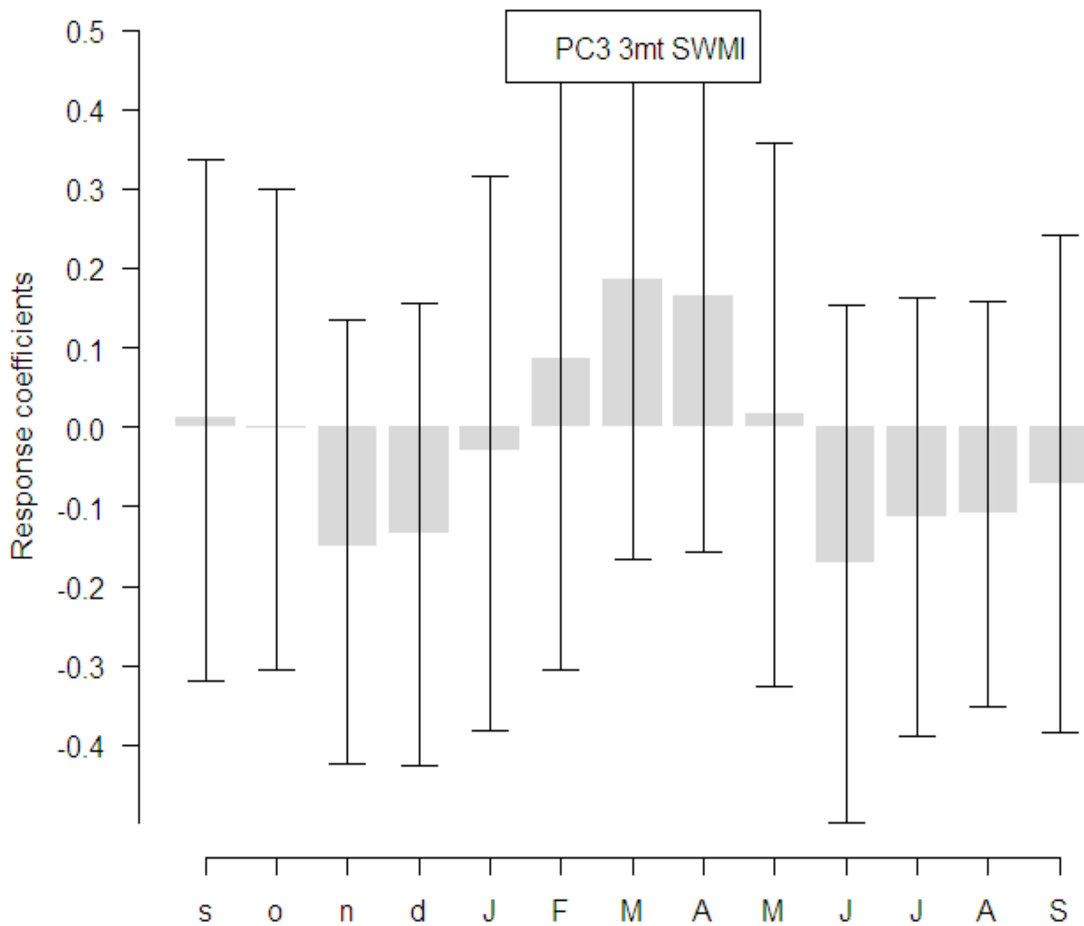

Figure 57 PC3 southwest monsoon index three month grouped response coefficient

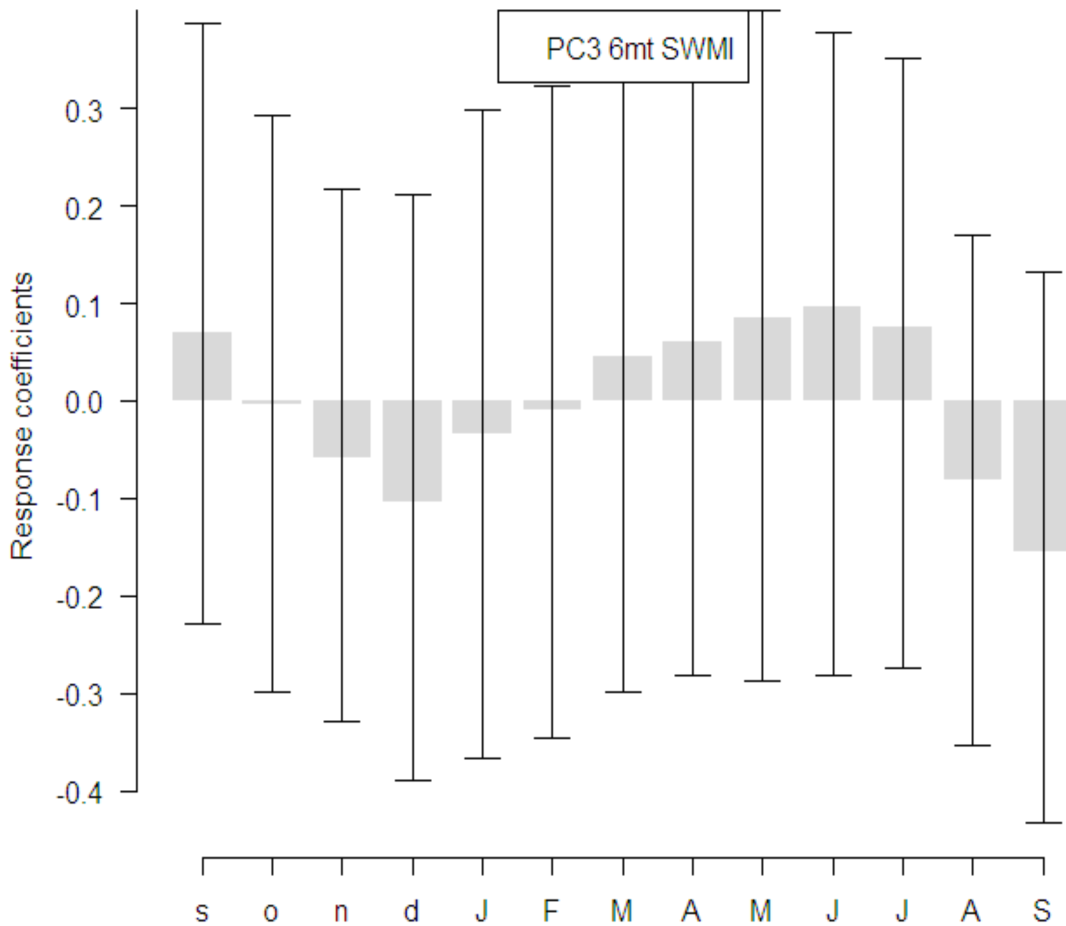

Figure 58 PC3 southwest monsoon index six month grouped response coefficient

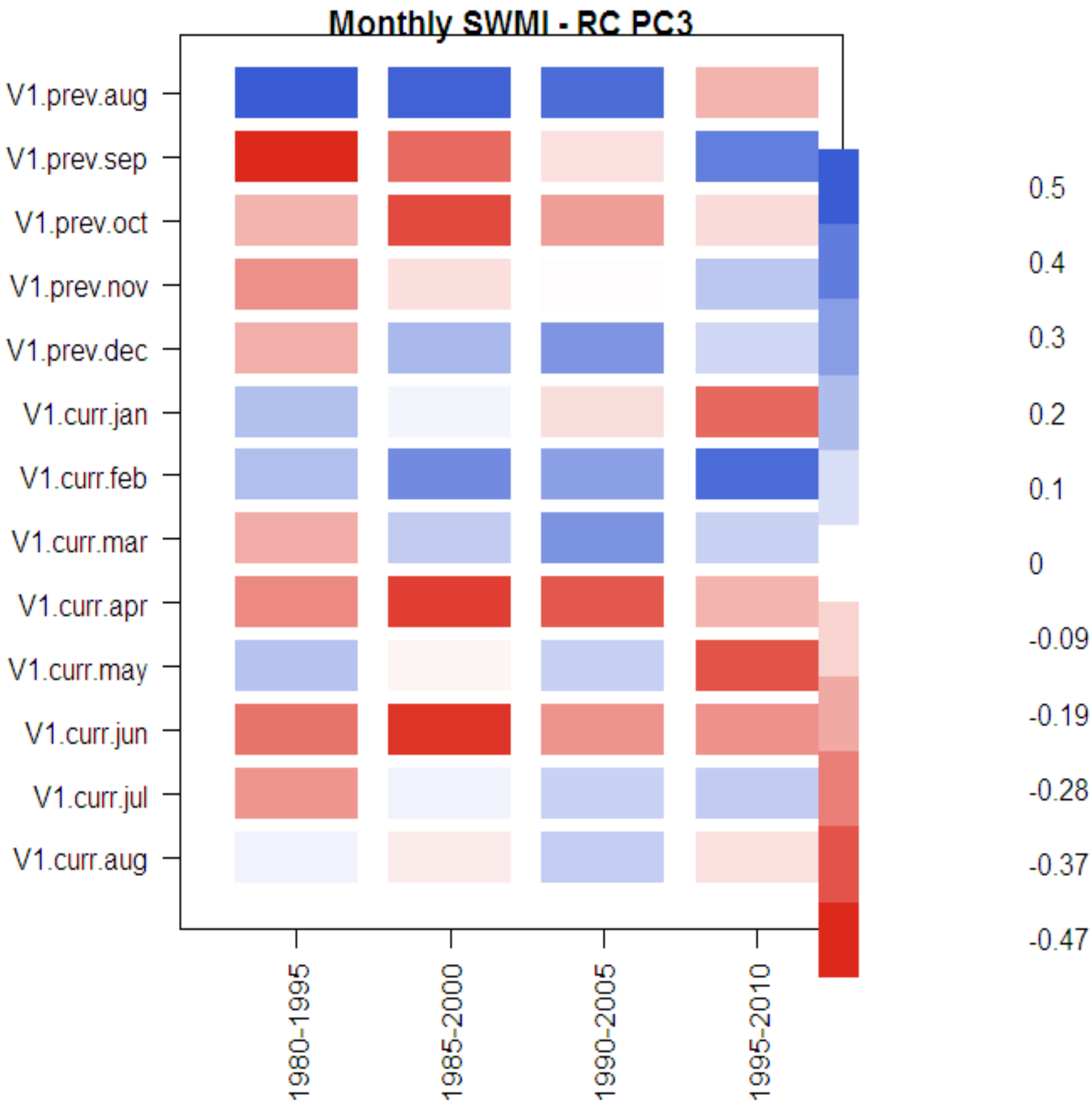

Figure 59 PC3 southwest monsoon index monthly response coefficient over time

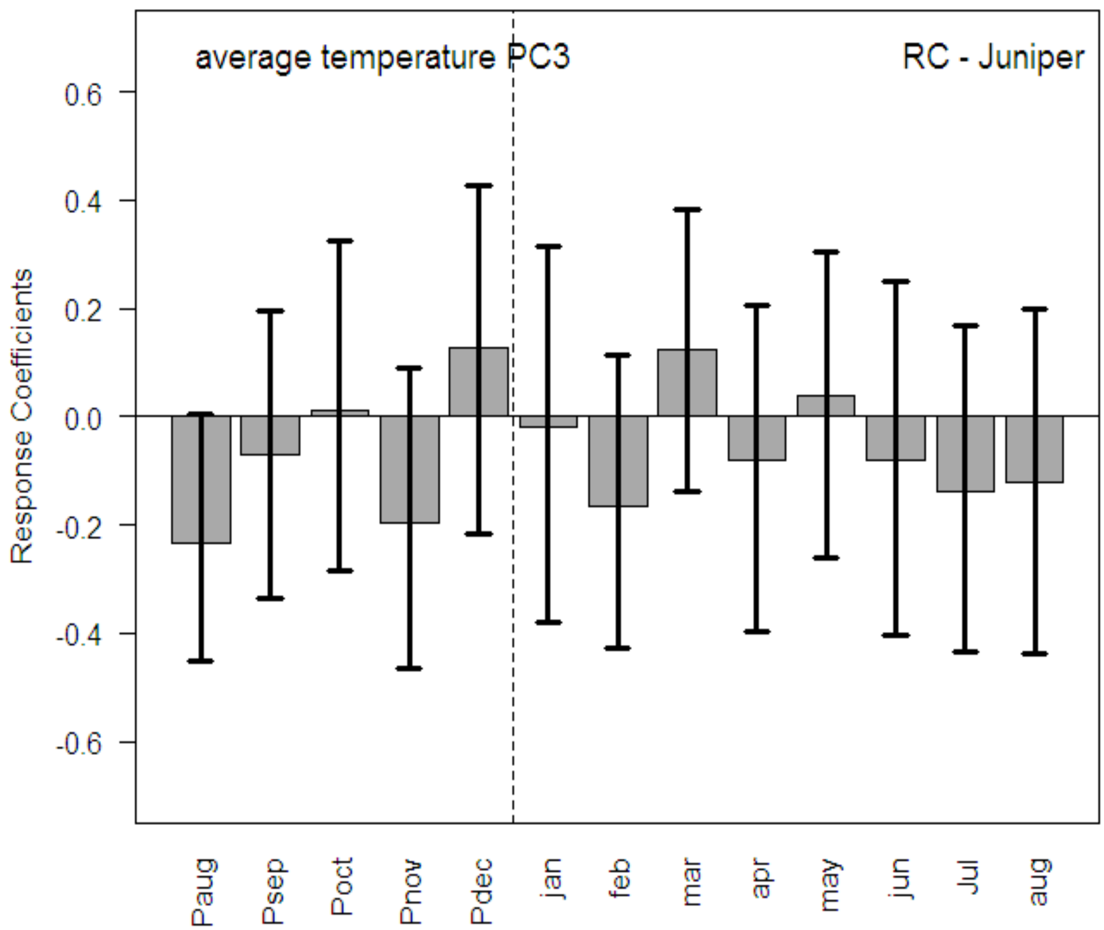

Figure 60 PC3 average temperature monthly response coefficient

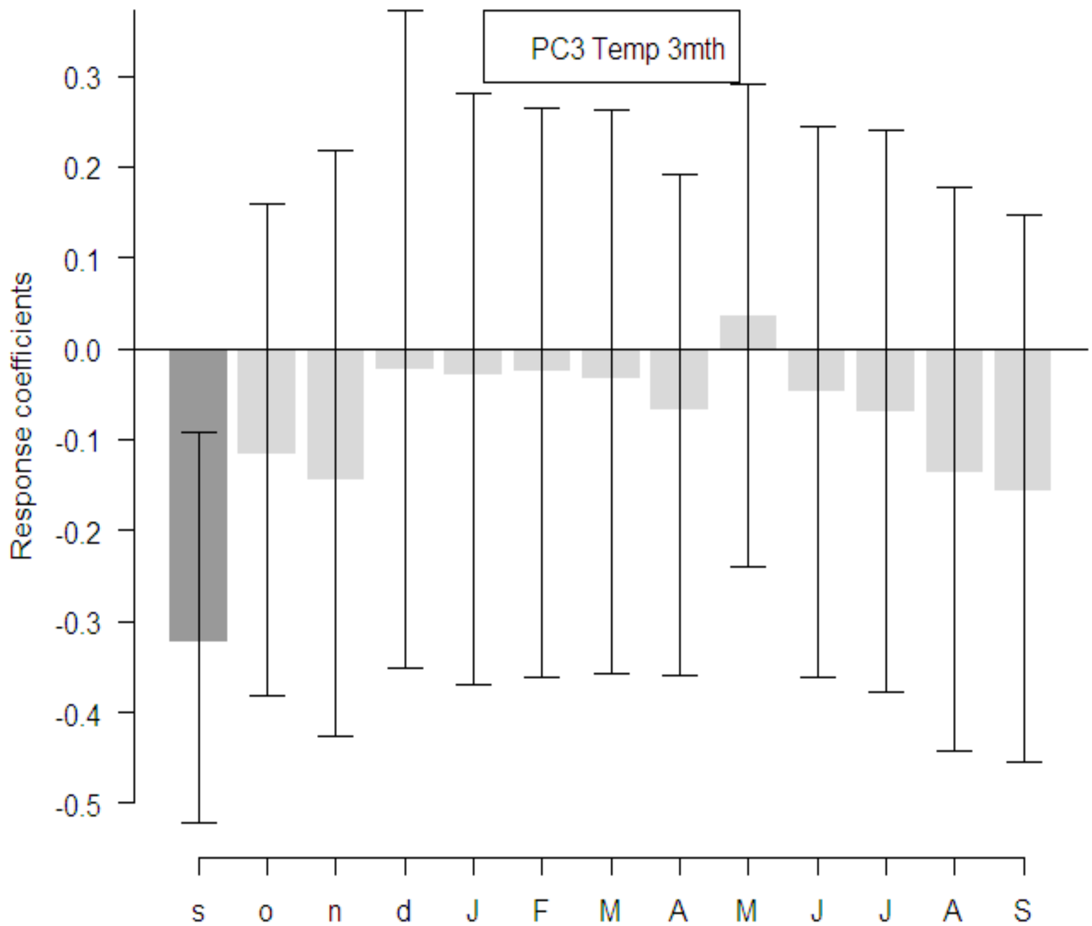

Figure 61 PC3 average temperature three month grouped response coefficient

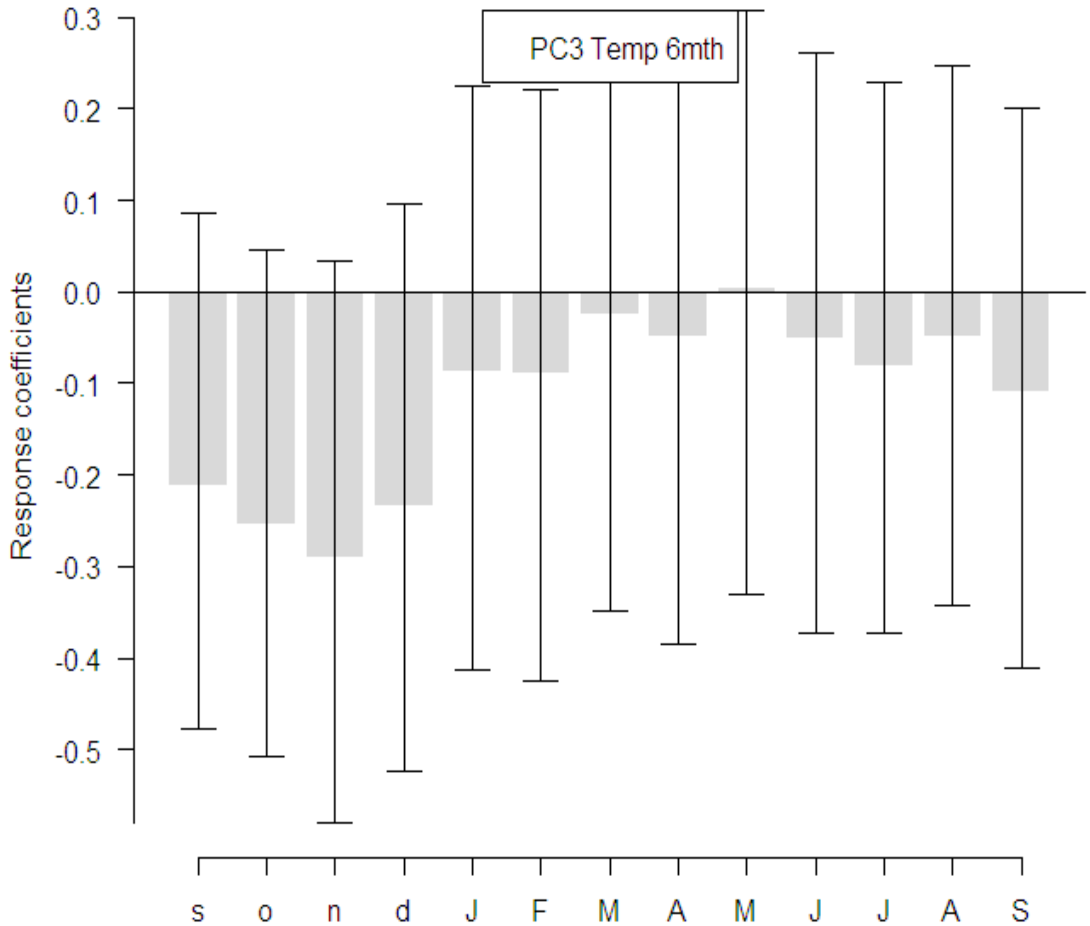

Figure 62 PC3 average temperature six month grouped response coefficient

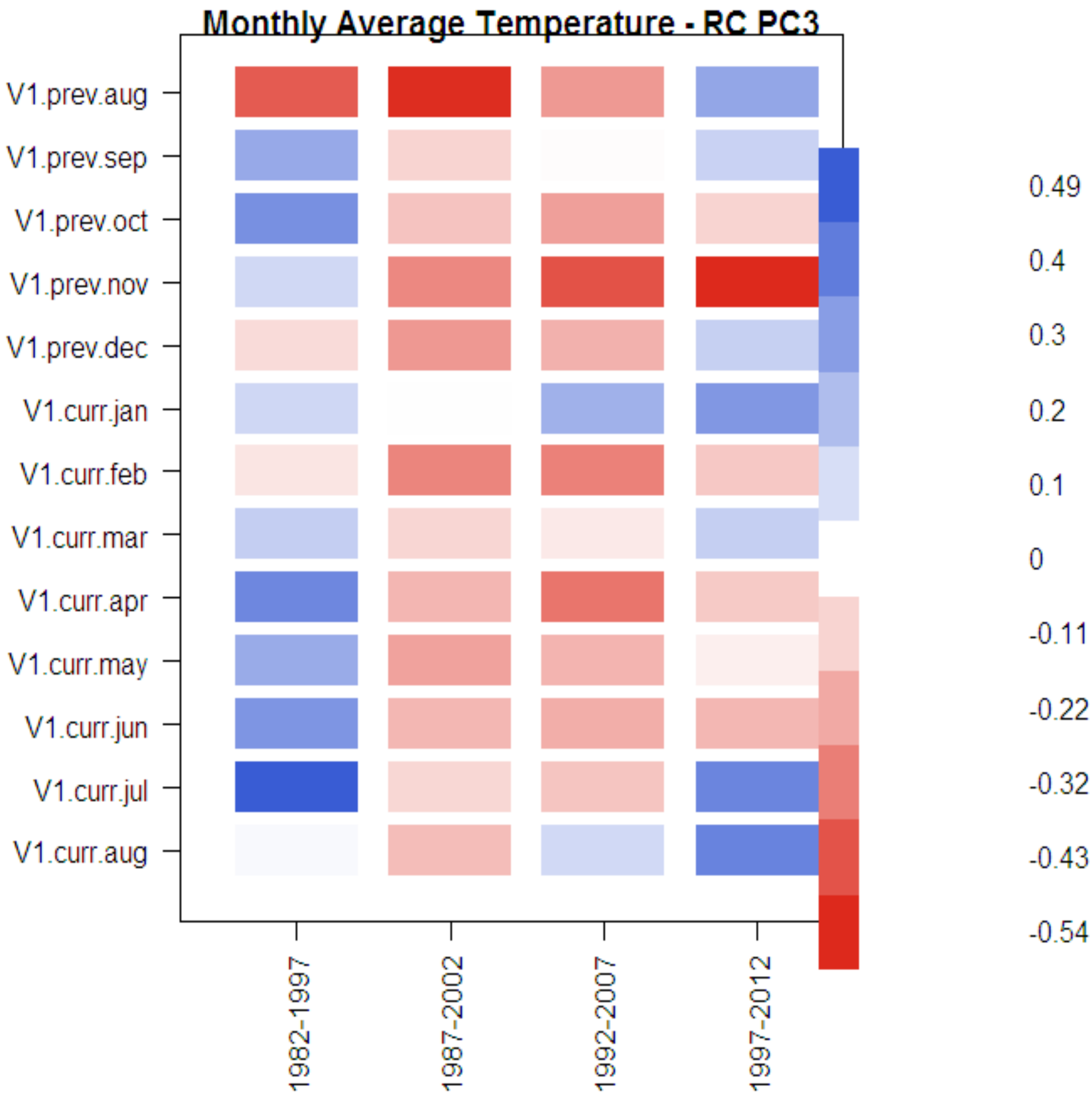

Figure 63 PC3 average temperature monthly response coefficient over time

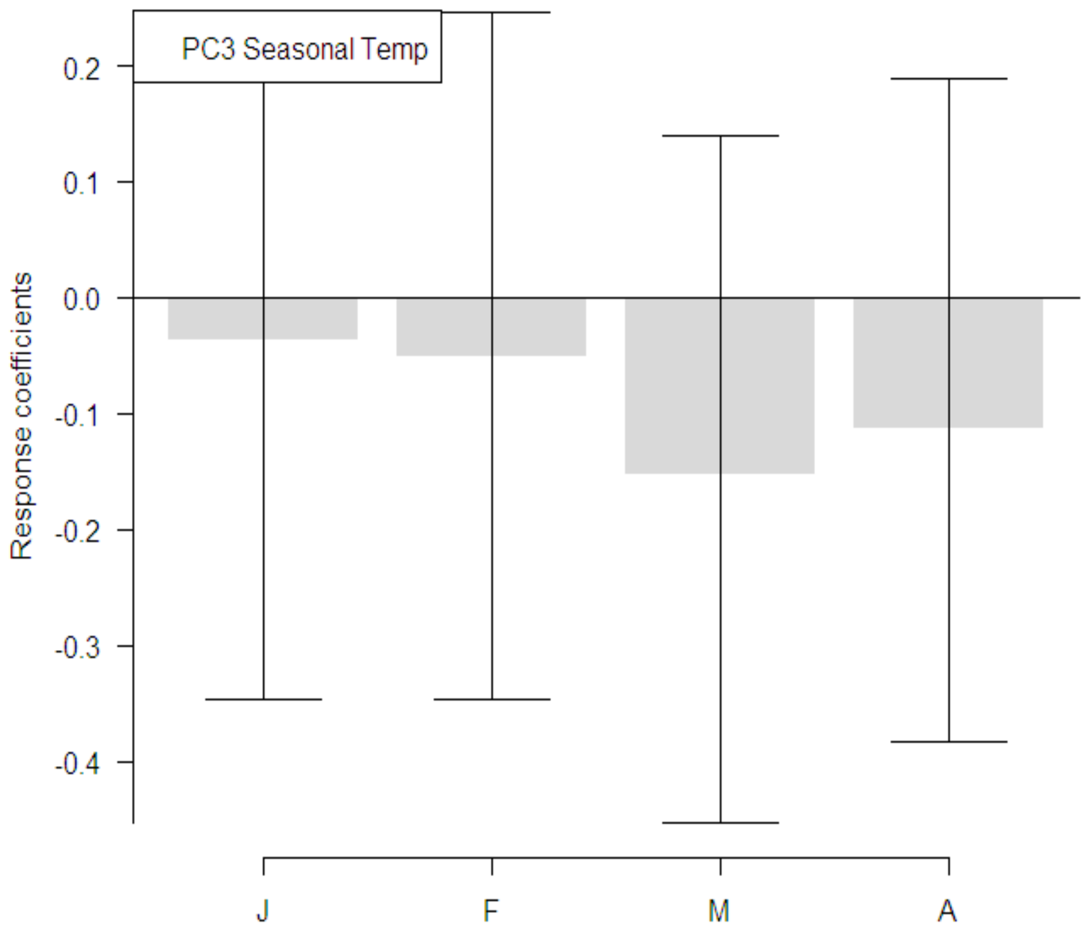

Figure 64 PC3 average temperature seasonally grouped response coefficient

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